APPLICATON OF SGC-RP TECHNIQUE FOR DEVELOPMENT OF AERODYNAMIC MODELS

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Partial Fulfillment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

by

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CERTIFICATE

This is to certify that the work contained in the thesis entitled, "**Application of SGC-RP technique for development of aerodynamic models**" has been carried out by L.Srinivas (Roll No. 9710519) under our supervision and that this work has not been submitted elsewhere for a degree.

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NOMENCLATURE

C	Chord length of wing (mm)
C_D	Coefficient of drag
C_N	Coefficient of lift
D	Diameter fuselage (mm)
D	Drag force (N)
f	Maximum stress (N/mm^2)
I	Moment of inertia (mm^4)
M	Bending moment (N-mm)
N	Lift force (N)
P	Atmospheric pressure (N/mm^2)
r	Y Co-ordinate for nose profile (mm)
R	Radius of curavature of wing profile (mm)
R	Gas constant (kJ/Kg ^{0}K)
S	Model plan area (mm^2)
T	Atmospheric temperature (^{0}C)
u	Parameter for nose profile
v	Wind speed (m/sec)
x	X Co-ordinate of nose profile (mm)
α	Angle of attack
ρ	Density of air (Kg/m^3)

ABSTRACT

Rapid prototyping is a group of newly emerging technologies to produce prototypes for checking conceptual design and preliminary testing of models. Among all, Cubital's Solid Ground Curing is one of the most capable RP technology with unique abilities like producing assemblies, nesting of parts and create them in a single run, and producing parts with self support structure. In the present work, an extensive effort has been put to produce prototypes of good quality by improving process parameters on a newly established Cubital's Solider 4600 at CAD-P lab, IIT-Kanpur.

The benefits to any field using RP models are many. One would be the ability to experiment with physical objects of any complexity in a relatively short period of time. In the present work, the feasibility of using RP models for wind tunnel testing in aerodynamic analysis has been examined. For this purpose, after creating CAD model for a particular aerodynamic model Agard-B, RP model has been created using Cubital's RP system. Wind tunnel testing has been done on the RP model, for comparing the results with the available test results from the metal model. The results, which were obtained from the testing, were quite satisfactory even though there were some differences in comparison. Besides this, before going for actual testing, Finite Element analysis has been used to check the maximum stresses, to which the test model would be subjected under wind tunnel test conditions.

Chapter 1

INTRODUCTION

1.1 Rapid Prototyping - A Review

Prototyping or model making is an age-old practice. The intention of having a physical prototype is to realize the conceptualization of a design. Thus, a prototype is usually required before the start of the full production of the product. In designing a new product, after the component requirements and evaluation criteria were established, the search for good rapid manufacturing methods began. Among all, Rapid Prototyping is one of the modern groups of technologies, which generate three-dimensional solids mostly using additive processes in which objects are fabricated by joining particles or layer of raw materials. These technologies target one of the most costly and time-consuming stages of new product design, and prototype development. Over past decade, not only has the performance of Rapid Prototyping systems been substantially improved, their rapidness has helped production engineers to accelerate production cycles, and their capability has provided designers with unique opportunities to create very complex geometric shapes. Normally, all Rapid Prototyping systems produce models in plastics. If a metal part is really necessary, the plastic model can be transformed by variety of molding techniques to a metal prototype for further study. In addition to this, multiple prototypes can now be reproduced more economically by using the Rapid Prototyping part as a master pattern for creating molds or soft tooling. Thus, Rapid Prototyping bridges gap between the design and manufacturing stages of a new product and helps to speed-up and automate the verification and tooling phase of the product development cycle.

1.2 Model Making - A Review

It is certainly true that engineers need a quick and easy way to verify designs and fix any problems before they proceed with tooling and production. Here prototyping takes great importance. The most time consuming and costly stage of a new product development is making a physical model or prototype of a design

concept. Prototyping allows a designer to check the function and appearance of a part. The traditional methods generally used in industries are Casting, Forging and Machining. The procedure for traditional method of prototyping involves conceptual designing, drafting, model manufacturing and inspection. This requires Pattern/Die-Making, which are made-up of wood, wax, plaster of paris, etc. But, Pattern/Die-Making needs high human skills and experience, which is main drawback of traditional methods. Complex parts having intricate shapes cannot be manufactured easily. So, there remains a geometrical inaccuracy in the prototype, which leads to inaccurate results. Apart from geometrical inaccuracies, traditional methods (CNC) require special tools, jigs, fixtures and special purpose machines, which increases the cost of the end product and also the time taken to the market.

During the last decade, a class of technologies has emerged by which a computer-aided design file of an object can be converted into a physical model through special sintering, layering or deposition techniques, which are variously called as Rapid Prototyping (RP), Solid Free-Form Fabrication or Automated Fabrication. The major application of this technology is the early verification of product designs and quick production of prototypes for testing.

1.3 Fundamentals of Aerodynamics

To give a brief picture about aerodynamic fundamentals, aerodynamic forces and coefficients & coefficient curves and their importance are discussed under this heading.

1.3.1 Aerodynamic Forces and Coefficients

The only two ways that air mass and the airplane can act upon each other are shown in Fig.1.1. As the aircraft moves forward, the air molecules are pushed aside. This causes relative velocity of air to vary about the aircraft. In some places, mostly towards the nose, the air is slowed down. In other places the air is speeded up relative to the freestream velocity. According to the Bernoulli's equation, the total pressure (static plus dynamic) along subsonic streamline remains constant. If the local air velocity increases, the dynamic pressure has increased, and hence the static pressure must decrease. Similarly, a reduction in local air velocity leads to an increase in static

pressure. Thus, the passage of the aircraft creates varying pressures around it, which push on skin as shown in Fig.1.1.

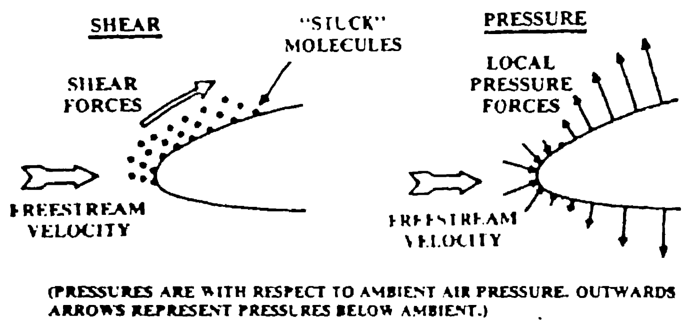


Fig.1.1: Origin of Aerodynamic Forces

In fact, lift is created by forcing the air that travels over the top of the wing to travel faster than the air, which passes under it. This is accomplished by angle of attack of the wing. The resultant difference in air velocity creates a pressure difference between the upper and lower surfaces of the wing, which produce the lift that supports the aircraft.

If the air molecules closest to the aircraft skin are moving with it, there must be slippage (or "shear") between these molecules and nonmoving molecules away from the aircraft. "Viscosity" is the honey like tendency of the air to resist the shear deformation, which causes additional air near the aircraft skin to be dragged along with the aircraft. Force required to accelerate this "boundary layer" air in the direction the aircraft is travelling, producing skin-friction drag. The drag on the wing includes various other components like profile drag, camber drag, skin friction drag, and drag-due-to lift etc.

All aerodynamic lift and drag forces result from the combination of shear and pressure forces. The lift force is perpendicular to the flight direction while the drag force is parallel to the flight direction.

Lift and drag forces are usually treated as non-dimensional coefficients as defined by the following equations.

$N = q\,S\,C_N$

$D = q\,S\,C_D$

1.3.2 Coefficient Curves

The importance of calculating coefficients is shown by discussing two of the coefficient curves briefly as below.

Drag Polar

Fig.1.2 illustrates the drag polar, which is the standard presentation format for aerodynamic data used in performance calculations. The drag polar is simply a plot of the coefficient of lift Vs coefficient of drag. It has an approximately parabolic shape as shown in figure. In this curve, the angle of attack, which is the angle between the axis line of the given model and the direction of the flight, is indicated by tic marks along the polar curve.

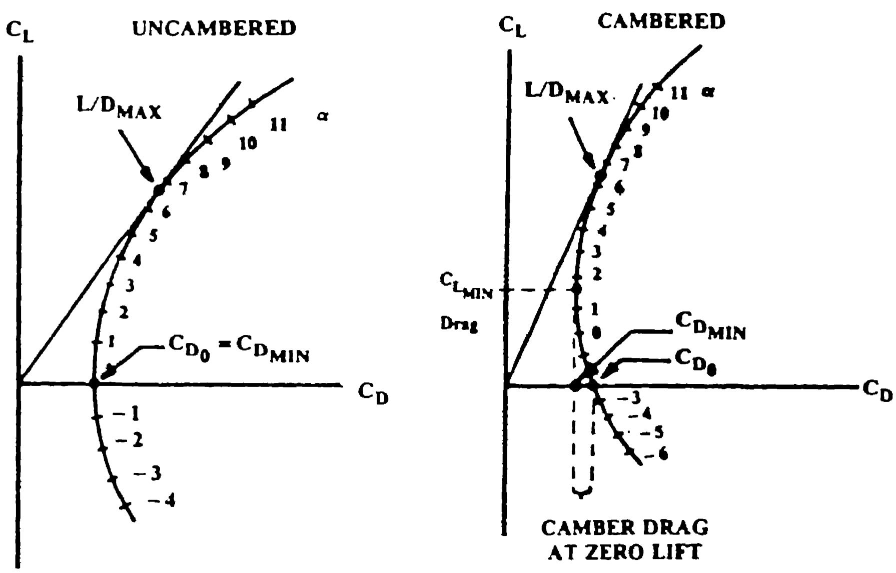


Fig.1.2: Drag Polar

From the curves, it can be observed that for an uncambered (2D) wing, the minimum drag occurs when the lift is zero. But for a cambered wing, the minimum drag occurs at some positive lift.

Lift Curve

Fig.1.3 shows typical wing lift curves. From this curve, it can be observed that the uncamberd (2D) wing has no lift at zero angle of attack, while the cambered (3D) wing has a positive lift at zero angle of attack. Maximum lift is obtained at the "stall"

angle of attack, beyond which lift rapidly reduces. When the wing is stalled, most of the flow over the top has separated. Thus, maximum coefficient is critical in determining the aircraft weight.

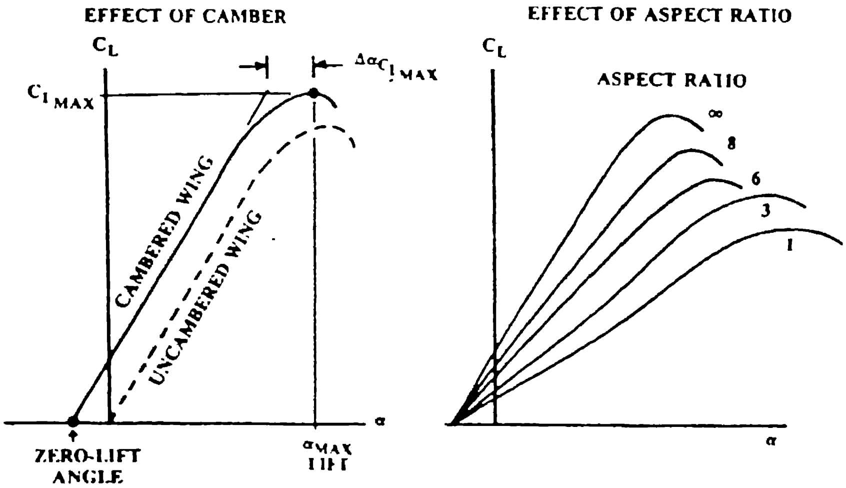


Fig.1.3: Lift Curves

The lift curve slope is needed during conceptual design for three reasons.

1. It is used to properly set the wing incidence angle. Wing incidence angle influences the required fuselage angle of the attack during take-off and landing.
2. The methodology for calculating drag-due-to-lift for high performance aircraft uses the slope of the lift curve.
3. Lift curve is used for longitudinal stability analysis.

1.4 Aerodynamic Applications of Models

Experimental information useful for solving aerodynamic problems maybe obtained in number of ways, among them wind tunnel testing is one alternative. Despite the recent development of sophisticated computer hardware and software to refine aerodynamics and improve aircraft performance, the present day aerospace industry relies on experimental wind tunnel test data to verify the performance of new aircraft design. Therefore, the creation of many wind tunnel models is usually involved in the development of new aircraft. For faster new product introduction aerospace companies are interested in reducing time it takes to make wind tunnel models. The increased capabilities of Rapid Prototyping Technologies have made them attractive

and an alternative to traditional Numerically controlled (NC) machining in the fabrication of wind tunnel model components.

Due to desired performance during wind tunnel tests, all wind tunnel models have three strict requirements: dimensional accuracy, surface finish and material strength. For a model to be qualified for wind tunnel tests, the surface profile dimensional tolerance should be within a particular range and depends upon the method of manufacturing. Since, the surface finish of a wind tunnel model has an influence on the stability of the boundary layer during testing, its specification should be within a particular limit and it depends on the method of manufacturing as well as material properties. During wind tunnel test, mechanical stress is usually present on the wind tunnel model components and it varies according to the wind speed. So, for the wind tunnel testing the properties of the material used have a great impact on the suitability of material for model making.

1.5 Statement of Problem

Establishing the CUBITAL's Solider 4600 system at IIT Kanpur and studying various parameters of the system for improving model quality. Besides this a study was undertaken to determine if Rapid Prototyping (Solid Ground Curing) method could be used in the design and manufacturing of low speed wind tunnel models in the direct testing applications for preliminary aerodynamic assessment of future launch vehicle configurations and see if this method would reduce model fabrication time while providing models of high enough fidelity to provide adequate aerodynamic data and of sufficient strength to survive in the test environment. Rapid Prototype method utilized to construct wind tunnel model was Solid Ground Curing (SGC) using Solimer as a build material.

For this purpose, a comparative study of the results from the wind tunnel tests of the Rapid Prototyping Model against Standard Metal Model was done to check the feasibility of Rapid Prototyping (SGC) for wind tunnel testing of aerodynamic models. In addition to it, an FEM analysis has been done on the Rapid Prototyping model to find out the optimal loads, which we can apply during testing. The plan was to determine if the aerodynamic characteristics of a generic vehicle would be effected by

surface finish and other material properties. Also studied were the ease of manufacturing of the parts as compared to a standard metal wind tunnel model.

1.6 Organization of Thesis

This thesis comprises of five chapters. It is organized in the following manner.

CHAPTER 1 gives a general overview of the Rapid Prototyping Technology and Aerodynamic Testing of wind tunnel models.

CHAPTER 2 explodes the Solider 4600 Rapid Prototyping System and gives all technical information related to it.

CHAPTER 3 contains various steps, which were followed for the wind tunnel model design and development.

CHAPTER 4 contains wind tunnel and FEM analysis procedures, results from these tests and comparative analysis of the results.

Chapter 2

SGC- RP PROCESS

2.1 System Overview and Architecture

The Solider 4600 is a fully automated Rapid Prototyping System and it employs patented Solid Ground Curing technology. In this technology no tooling or support structure is required, Solid Wax filler replaces the uncured resin to provide continuous solid support for any geometrical configuration. This uses liquid resin for building model and Solid Wax as raw material for creating any geometry quickly and accurately. In this, 3-D models can be produced in two stages; they are Data Preparation and Model Production. In the first stage digital files are analyzed and converted into separate layer files and transferred to MPM system. In the second stage, the actual model building takes place by controlling the different parameters and coordinating different functional units of the system by the Process Controller. The block diagram of the Solider 4600 system is shown in Fig.2.1.

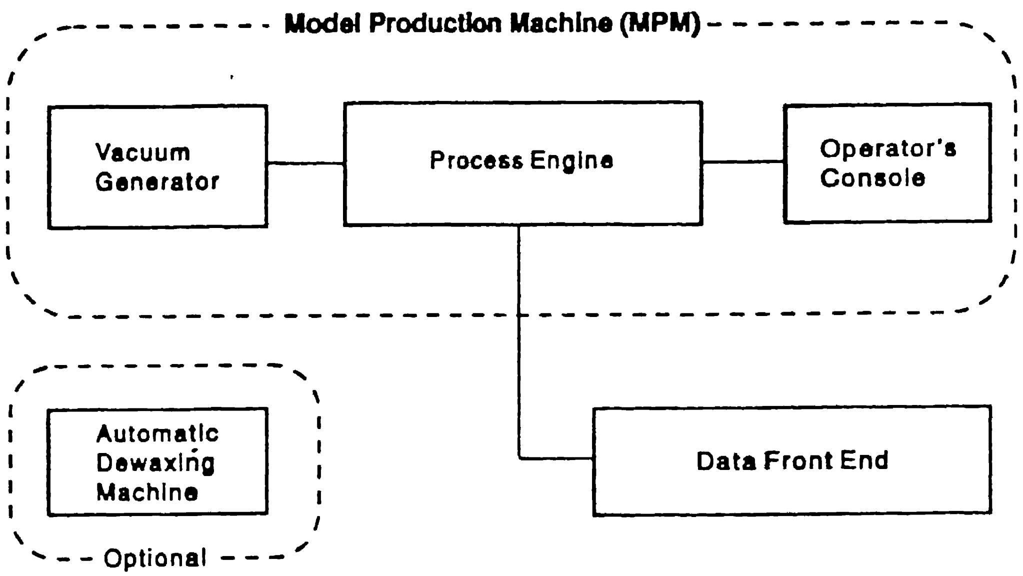


Fig.2.1: Solider 4600 System block diagram

The main components of the Solider 4600 system are,

- Data Front End (DFE)work station
- Model Production Machine (MPM)
    - Process Engine
    - Operator's Console
    - Vacuum Generator
- Automatic Dewaxing Machine (Optional)

DFE Workstation

The Data Front End workstation serves as an interface between the designer's CAD file and the Model Production Machine (MPM). The DFE Workstation reads and checks the CAD data files, makes modifications and corrections when necessary, and prepares them for production. The DFE Software provides tools for editing, copying, moving, scaling, and rotating objects. In editing process, any redundant information can be removed, flaws are corrected, and more effective-three dimensional representations are produced for objects before actual production. After editing files, objects, which are required to produce in same run are arranged in such a way that, the total height required to produce the run should be minimum. Once nesting of the parts is over consolidate file will be created. Using this file, the DFE mathematically slices objects of the file into thin layers and sends raster data of the layer to the MPM.

Model Production Machine

The MPM consists of the following two units

Process Engine The Process Engine consists of a heavy frame on which many functional units are mounted, which participate in the Mask Generation and Model Build Cycles. The actual 3-D object is produced in the Process Engine through the coordinated action of the different functional units.

Operator's Console The Operator's Console provides intervention for the operator for controlling different parameters in the production process. The Operator's Console includes CRT monitor and keyboard for displaying the status of the functional units and permits inputting operator's instructions, Operator Panel for indicating the over all machine error status and includes emergency push buttons, and Video Monitor, for displaying the glass plate at the UV exposure station.

Vacuum Generator

The Vacuum Generator provides vacuum alternatively for wiping uncured resin and removing plastic chips from the milling operation.

Automatic Dewaxing Machine (ADM)

The ADM is an optional and a stand-alone unit for quickly removing filler wax from the completed job. For desolving wax it uses hot citric acid solution, which is sprayed on the workpiece by revolving nozzles.

2.2 Principle Of Operation

The total process of making the model, once the layer data has sent to the machine includes two cycles. The first cycle is the Mask Generator Cycle and the second cycle is the Model Building Cycle. These two cycles operate in such a way that; there is an overlap on each other when they come to the UV Hood.The Cyclic Diagram of the principle of operation of the system is shown in Fig.2.2.

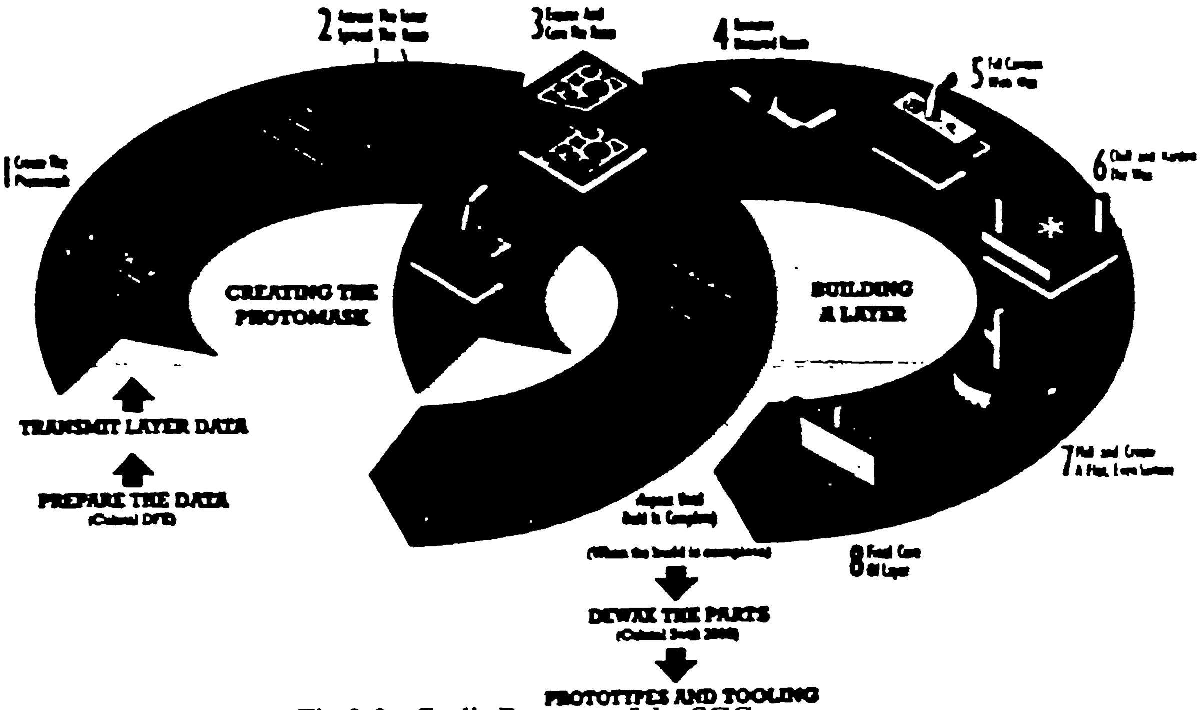


Fig.2.2: Cyclic Diagram of the SGC process

The various steps in these two cycles are as follows.

Mask Generator Cycle

The entire Mask Generator Cycle is monitored and controlled by the internal computer called the Process Controller. The cycle begins and ends with the Mask

Frame underneath the Primary UV Station where a generated mask is positioned above a layer of liquid resin spread on the Model Tray. The steps in the cycle are:

1. When the Mask Frame is over the Model tray UV light passes through the transparent areas of the mask, and hardens the resin underneath.
2. After exposure, the mask Frame moves left to the Toner Unit. While in motion, a Rubber Blade wipes toner off the Mylar Sheet and collects it for re-use. The Mask Frame moves to the Ionographic Unit, where the Erase Rod neutralizes electrostatic charge. The Mask Frame moves to its extreme left position and stops, there it waits to produce the next mask.
3. For next mask generation, When the Mask Frame passes over the Ionographic Unit, it places electrostatic charge on areas of the Mylar Sheet that are to attract the toner. The shape of these areas is determined by the data received from the Process Controller.
4. The Mask Frame with the charged Mylar Sheet moves to the Toner Station, where Toner is attracted to the charged areas of the mask. Then, it goes to the UV Hood and waits there until the Model Tray comes for the primary exposure.

Model Building Cycle

The Model Builder produces a three-dimensional model layer by layer. The shape of each layer is determined by a mask generated for that layer. The entire Model Building Cycle is monitored and controlled by the Process Controller. Th cycle begins and ends at the resin station where a new layer of resin is added. Except during UV exposure, the processing is carried out while the model tray is moving underneath the functional units. The steps in adding a new layer to the model are:

1. Layer of resin added to the model at the resin station. A thin layer of liquid resin is applied.
2. Layer of resin exposed to UV light at the primary UV station. Model tray moves to the primary UV station. The mask, located between the UV light and the model tray, is already prepared with toner to define the shape of the layer. UV light passes through the transparent areas of the mask and hardens the resin underneath.

3. After the resin is cured at the UV station, uncured resin is removed at the wiper station. An aerodynamic wiper plate creates a strong air jet that lifts off the uncured liquid resin. A suction slit removes the lifted resin, revealing the wax in the model.
4. The remaining resin is cured at the UV station in the secondary exposure. UV light floods the layer to complete the hardening of the resin representing solid areas in the layer.
5. Layer of wax is added to the model at the wax station. A layer of melted wax, that covers the cured resin and fills voids, is applied.
6. Wax layer is then solidified at the cooling station. A metal plate cooled by water chilled to 4°C presses down on the wax layer and solidifies it.
7. A new layer is milled to the specified thickness at the milling station. Rotating diamond tipped blades mill away excess wax and resin to leave a new layer at the specified thickness.

The model building cycle starts again to produce a next layer.

2.3 DFE Software

As mentioned earlier, the 3-D model creation contains two steps, Model Preparation and Model Production. The Model Preparation can be done through the graphical interface provided by Cubical Inc., the DFE (Data Front End) software, in four stages. They are explained hereunder.

Reception

Reception is used to import 3-D part data in industry standard file formats and converts into a SOLI file used for processing within the DFE software. The different input file formats, which are accepted by Reception includes STL (Binary & ASCII) and CFL (Cubical Faceted List) formats. In case, files which are in other formats than the mentioned ones are required to open in Reception, some translator are supplied with the DFE software, which convert any other file into CFL file.

Academy

Academy is a Solider DFE application that enables you to improve an actor's physical characteristics and repair the possible flaws in the SOLI file. Academy has four characteristics.

Interfacing: Introducing the actor into the academy and getting the information on its history and current state.

Editing: It involves geometric transformation (rotation and scaling), model cutting, widening and separation of actor items.

Corrections: It includes binding of nearby borders between two items or patching gaps in items.

Compression: It involves reducing the size of the data required to represent the actor either by uniting facets that are on the same plane, or by uniting nearby vertices.

Show

It collects and organizes a group of actors for a production run on the MPM. The following design goals can be met in Show.

1. Maximum number of actors can be placed in minimum height and volume by fitting them together efficiently as shown in Fig.2.3.
2. The surface quality can be optimized by orienting the walls and other major surfaces of the model parallel to the primary axes of the show volume.
3. It allows creation of complex structures, such as models or casting molds, by combining number of actors into compound assemblies.

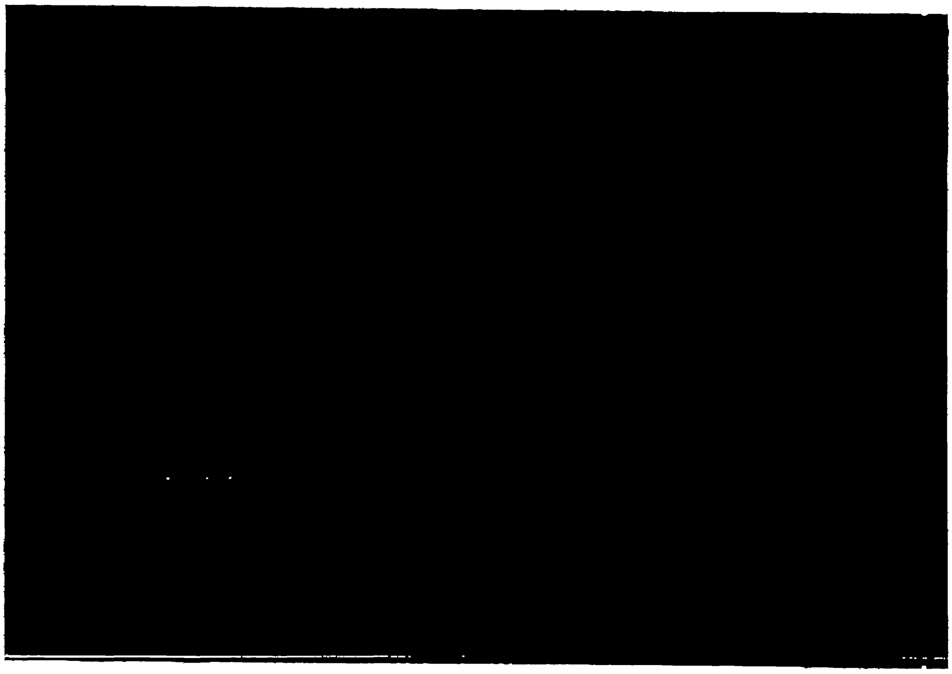


Fig.2.3: Nesting of parts in Show

Production

This application of DFE allows two major operations.

1. **Preview:** The production file to determine if any actors need to be modified or repositioned.
2. **Submit:** This is used to submit the production file to the MPM for production. The data for each layer is stored in a separate file called a CDT (Cubical Data Transfer) file and this is sent to the machine.

2.5 MPM Software

The heart of the model production machine is an 80386 based process controller working under a RMX operating system. Solider is the software package that controls the MPM operations. The data flow diagram for different units of the system is shown in the following Fig. 2.4.

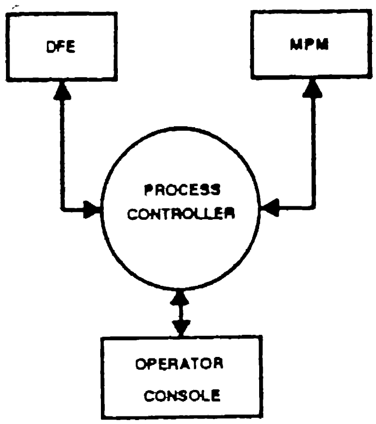


Fig.2.4: Data Flow diagram

The functions of the Process Controller are,

- Receives input from Data Front end
- Requests and receives input from the Operator Console Keyboard
- Receives input from MPM functional units
- Controls and Coordinates all model building procedures
- Controls and monitors the motion of the Model tray and Mask support frame.

Data displayed by the process Controller on the monitor allows the operator to monitor the modes and parameter settings of all machine units. The MPM software package can be explained under the following sub-headings.

2.4.1 Monitor Screens

In the Solider Software two screen layouts are available. First one is the Main Screen, which is displayed when Solider is loaded and the Second one is the Refresh Screen, to display this we have to press <R>.

Main Screen

The following Fig.2.5 shows a typical Main Screen layout for a system in the active mode, which is divided into eight major sections.

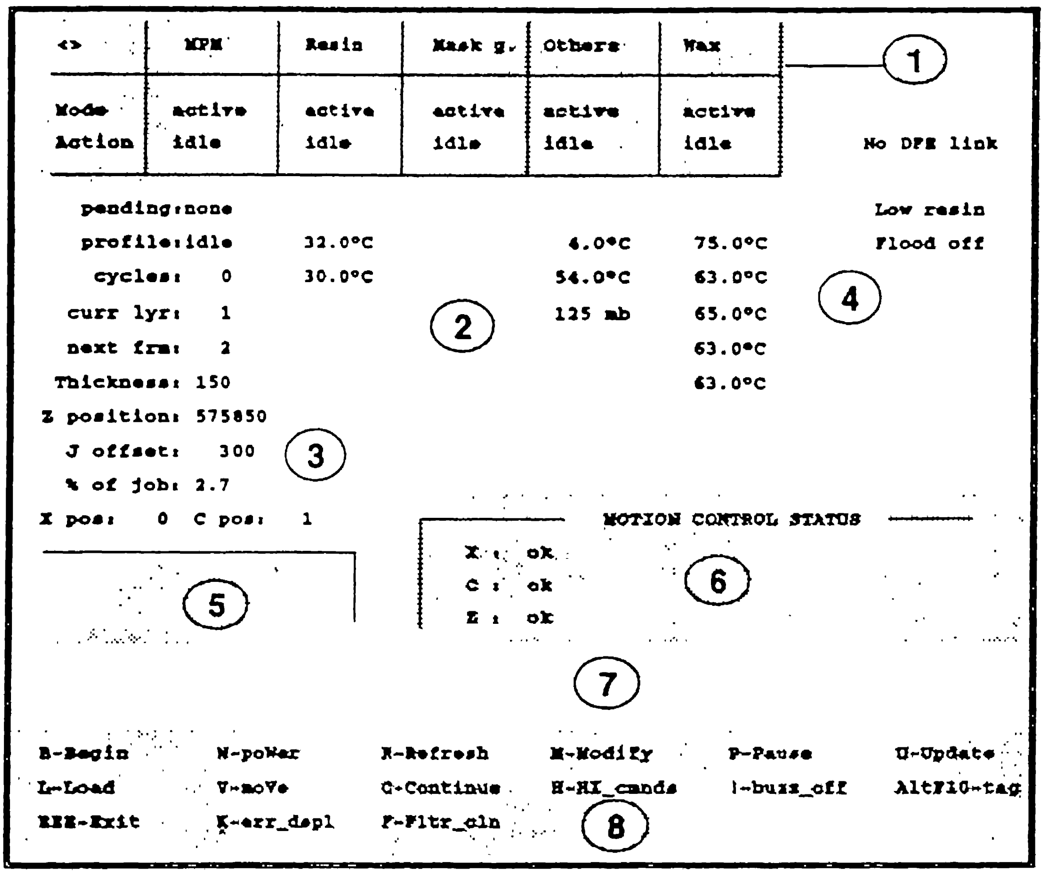


Fig.2.5: Main Screen diagram

The first major section, Modes and Action display, shows activity status of the MPM and its different functional units. The information appearing for the MPM should

be considered the major and most meaningful indication of the machine Status. The second line in the Modes and Actions display shows the current mode of the MPM and its units. A mode describes a status or functional capability of the unit. The possible modes of the MPM and its different functional units are given briefly as follows,

Off mode No part of the machine is powered on, except the computer and the operator console

Standby mode The Resin and the Wax systems are with in operating temperature range. No power is supplied to other units.

Active mode The Resin and Wax units are within their respective operating temperature range. The Cooler , the Flood and the Motion units are powered on.

Working mode The MPM is performing an on-going machine operation or a file load/Save.

Pause mode The pause mode is switched to automatically at the completion of the requested number Normal or Long Profile cycle. When machine is in Pause mode means machine is idle.

Error mode The MPM or any functional unit is placed into the error mode when a requested action or activity cannot be executed or completed because the Process Controller (software) has detected a malfunction.

Waiting mode A unit will be placed in the waiting mode if one of its heating loops is still out of working range when a MPM mode change is requested.

Working mode A unit can be in working mode only if the MPM is in working mode. In general, a unit is in working mode for a relatively short time.

The third line in the Modes and Actions display sections shows the activity of the MPM and the units. An action is a specific procedure or activity being carried out by the MPM or the units once they have reached a certain mode.

The second section which is Heat/Vacuum loops shows the temperature/pressure of MPM loops. In this comes, the temperature of resin in the Resin Applicator, pressure and temperature of vacuum developed in the Vacuum Generator and temperatures at different places in the Wax Unit.

The third section, which is model production display, shows the status of the current job. The different parameters in this section and their meanings are explained as follows, -

Pending: what the next mode MPM will be in after completion of current profile cycle

Profile: The profile currently being executed

Cycles: Number of times current profile is to be performed.

Current lyr: Number of layer currently being produced.

Next mask: Number of next mask to be received from DFE

Thickness: In Normal and Long profiles, layer thickness as defined by DFE. In delete profile, thickness of layer to be deleted.

Z position: Absolute Vertical position of Model Tray measured in microns.

J offset: Absolute height of last layer relative to the first layer of the current job, measured in microns.

% Of Job: Percentage of job completed.

X pos: Absolute horizontal position of Model Tray

C pos: Absolute horizontal position of Mask Support Tray.

The fourth section, which is Labels, appears in the right side of the Main Screen Display to highlight the status and activity of the software and certain MPM units.

The fifth section, which is Messages section, shows errors, warnings, and success message generated by MPM activity.

The Sixth section, which is the Motion Control Display, shows the status of the MPM motion axes. A motion error message in the Messages display will be accompanied by a specific message in the appropriate Motion Control Status Line.

The seventh section, which is Dialogue and Data Entry Display, shows user interface dialogue, system parameter, and data entered at the Operator Console.

The eighth section, which is the Keyboard Menu Display, shows the main keyboard menu. Detailed information on the commands accessed at the Keyboard are given under thee subheading “Keyboard Menu”.

Refresh Screen

The typical MPM Refresh Screen Configuration is shown in the following Fig.2.6. The Refresh Screen contains data not shown on the Main Screen, to display the Refresh Screen, press <R>. To return to the Main screen press any key.

```
SOLIDER

   MPM software version V2.2      dated : 11-MAR-1993 23:46:31.17
   Started at 03/12/93  00:05:19
   MOTION VERSION : 021192

rimary UV activations:    5221     Number of spreads to next bleed:   30
     mask generations:    5216     Enough resin for more than 00200 spreads
      Produced layers:    4242
        Last Z height:  575000
  last produced layer:     101
           TAG1 value:  591000
          TAG2 values:  590150/   0    (Current value should be 0101/+000)

                                                type any key to continue ...
```

Fig.2.6: Refresh Screen diagram

The main parameters and their meanings are explained as follows,

Last Z height: Absolute height in microns of the last produced layer as it was just before final milling of a delete or put wax profile.

Last produced layer: Number of last produced layer of current job.

TAG1 Value: Value of TAG1 in microns for Process Controller reference.

TAG2 Value: Z position in microns / layer number as recorded by Alt – F10 command.

Number of spreads to... Number of resin spreads left before automatic air bleed.

Enough resin for more... When resin level above sensor, minimum spreads remaining in the resin barrel.

(Current value should be) For the current height, what should be the current layer number.

2.4.2 Key Board Menu

The Keyboard is used by the operator to control and monitor MPM operations and to view and modify MPM parameters. The main Keyboard menu has the following items.

B-Begin	W-power	R-Refresh	M-Modify	P-Pause	U-Update
L-Load	V-Move	C-Continue	H-HI_Cmnds	!-buzz off	AltF10-tag
EEE-Exit	K-err_dspl	F-Fltr_cln			

Key Board Menu List

To activate a menu item, press the letter displayed at the beginning of the item. The various items and sub-items are briefly explained as follows.

B – Begin: The Begin command starts a predetermined sequenced of actions, called a profile that can be performed by the MPM. Press <B> to display the following Begin's submenu of pre-defined profiles.

0 – idle, 1 – norm, 2 – del, 3 – mask, 4 – cln, 5 – wax, 6 – long,, 7 – St_j, 8 – view, 9 – rec.

The available MPM profiles available with the Begin command described below.

Idle This is to switch off Mask Generator, Milling and Vacuum Generator units.

Normal (norm) The Normal profile is used to produce model layers using the flood unit.

Delete (del) The Delete profile is used to delete layers from the work-piece. The number of layers deleted is determined by the operator.

Mask The Mask profile is used to generate a new mask on the Mylar sheet and to check mask generator performance.

Clean (cln) The Clean profile is used to clean the Mylar Sheet and move the Mask Frame to the left end of the mask axis.

Wax The Wax profile is used to spread wax layers on the Model Table.

Long The Long profile is used instead of Normal for production in which the Flood unit is not used.

Start job (St_j) The Start job profile is used to deposit the base polymer on the PVC work-piece base.

View The View profile is used to examine the model table at any instant during job production without disturbing its sequence of production.

Recovery(rec) Recovery is used to resume production after emergency stop or failure during layer production. This procedure is necessary only when the process was interrupted before completion of the current layer.

R-Refresh: This command is for displaying the refresh screen.

M-modify: This command is for modifying the following parameters. Once we press <M>, the following submenu will be displayed.

Modify: N-Next layer F-Finger mask L- Layer resolution (for DELETE)

The importance of above mentioned parameters are as follows,

Modify Next layer To reset (modify) the next frame number, which will be received from the DFE.

Modify fingers mask To disable automatic mask quality control. So mask is produced even with low quality by using this command.

Modify Layer Resolution (Thickness) To set the layer thickness removed by the milling unit at each cycle of a Delete profile mainly to save time for deleting layers from the Model Table.

P-Pause: The Pause command is used to temporarily stop the execution of a profile. If Pause command is given in the middle of any cycle, the MPM will continue the profile execution until the next stop point.

U-Update: The Update command is used to examine and modify machine and motion parameters. By pressing <U>, thee following sub-menu will be displayed.

Select parameters to update: 1-Machine 2-Motion

Choosing option 1-Machine from the Update command submenu, a numbered list of the machined parameters will be displayed. For modifying any of these parameter values, enter the list index from the list. The parameter list is shown in the following Fig.2.7.

```
E D I T I N G    P A R A M E T E R S    F I L E   updated: 10.9.92

 1 - Get masks from DFE (1) or file (0)          :  1
 2 - Lower workpiece for view profile            :  200
 3 - 1 for diagnostic bleed (otherwise 0)        :  0
 4 - RESIN spread enable(1)/disable(0)           :  1
 5 - fast_heat set point [°C]                    :  32
 6 - dispenser set point [°C]                    :  30
 7 - Flood enable(1)/disable(0)                  :  0
 8 - First projecting interval [10ms]            :  600
 9 - COOL PLATE set point [°C]                   :  5
10 - Press(mill) set point [mb]                  :  120
11 - WAX spread enable(1)/disable(0)             :  1
12 - WAX melter heat enable(1)/disable(0)        :  1
13 - Melter set point [°C]                       :  75
14 - Tank set point [°C]                         :  63
15 - Pump set point [°C]                         :  65
16 - Hose set point [°C]                         :  63
17 - Applicator set point [°C]                   :  63

<Line index> - Edit line    Q - Quit    S - Save & Quit       8

Old Value of First projecting interval [10ms]  [400-700] : 600
Enter NEW Value :
```

Fig.2.7: Update Parameter List

L-Load: The Load command is used to load parameter and motion files after some modifications are done on any of these files .By pressing <L>, the following sub-menu will be displayed.

Select parameters file type : I-MACHINE P-PROCESS M-MOTION

According to the type of the file, which is required to modify, we have to select suitable option. The different files of the MPM will be discussed in the subsequent material.

W-Power: The power command is used to switch the system to the off, standing or active modes. By pressing <W>, the following sub-menu will be displayed.

Power : O-off S-standing A-active

C-continue : The Continue command is used to continue operation after executing the Pause command.

H-Hi : The Hi command is used to enter RMX (operating system) commands without exiting Solider software . In this section, RMX commands such as Dir and Aedit can be entered.

V-move : The Move command is used to change position or carry out homing on the Model Tray or the Mask Frame axes .Move command is valid only when the system is in the active mode or in error mode if the prior mode was active.

EEE-Exit : This command is used to exit Solider and return to RMX. This command will be activated by pressing <E> three times.

K-Display the current error log file: The K command displays the current error log file .This command available when MPM action is idle.

!-Beep-off : The beep off command stops the error warning beep until a new error message is generated .

<Alt><F10>-TAG: The TAG command is used to record layer height as TAG1 or TAG2. By pressing <ALT> <F10>, the following sub-menu will be displayed.

Select tag to set : 1-Tag1 2-Tag2

TAG1 is a reference point on the Z-axis of Model Table only and has no significance for MPM operation. TAG2is used by the Process Controller as a control reference point for layer production.

2.4.3 System Files

The operation of the MPM requires many files, among them following are the important ones:

SOLIDER : Solider is the main program file loaded into the process controller at startup to control the activities and motions of the MPM units.

DEF.PAR : The DEF.PAR file contains the parameters for the MPM units .If a save was made by the Update command, the new file will be loaded automatically.

BASE. MOT : The BASE.MOT file contains the principle parameters for the motion software, is not to be altered by the operator.

DEF.MOT : The DEF.MOT file contains parameters for motion software that can be altered by the operator.

TUNE.DAT: This file contains pressure curve & production parameters for the resin spread in relation to the Model Table velocity, when it moves under the Resin Applicator.

RESIN.LOG: This file contains a set of resin spread pressure distributions. By pressing Ctrl-M a new resin spread pressure distribution is loaded in this file after a layer of resin was applied over the Model Tray.

TRAJ_MOT.DAT: This file contains resin spread parameters, by changing them we can control the thickness of the resin layer.

2.5 Functional Units of The System

The various functional units of the system are classified according to their participation in the whole process, which contains Mask Generator Cycle and Model Building Cycle. The system front view and back view with various functional units are shown in the following Fig.2.8 and follows with, their description.

Mask Generator Cycle functional units

1)Motion Units:

The Motion Units move the mask from one station to another. They consist of the following major components.

Mask Frame. Mask Frame supports the mask and moves it to the stations.

Mask Motion Track. It guides the horizontal motion of the Mask Frame. The Track is a stainless-steel strip mounted horizontally on Process Engine Frame.

Horizontal Motion Drive. It is a direct-drive motor which moves the Mask Frame on the Mask Motion Track.

2) Mask Unit:

The mask determines the geometrical shape of the next layer added to the model. The components making up the Mask Unit are described below.

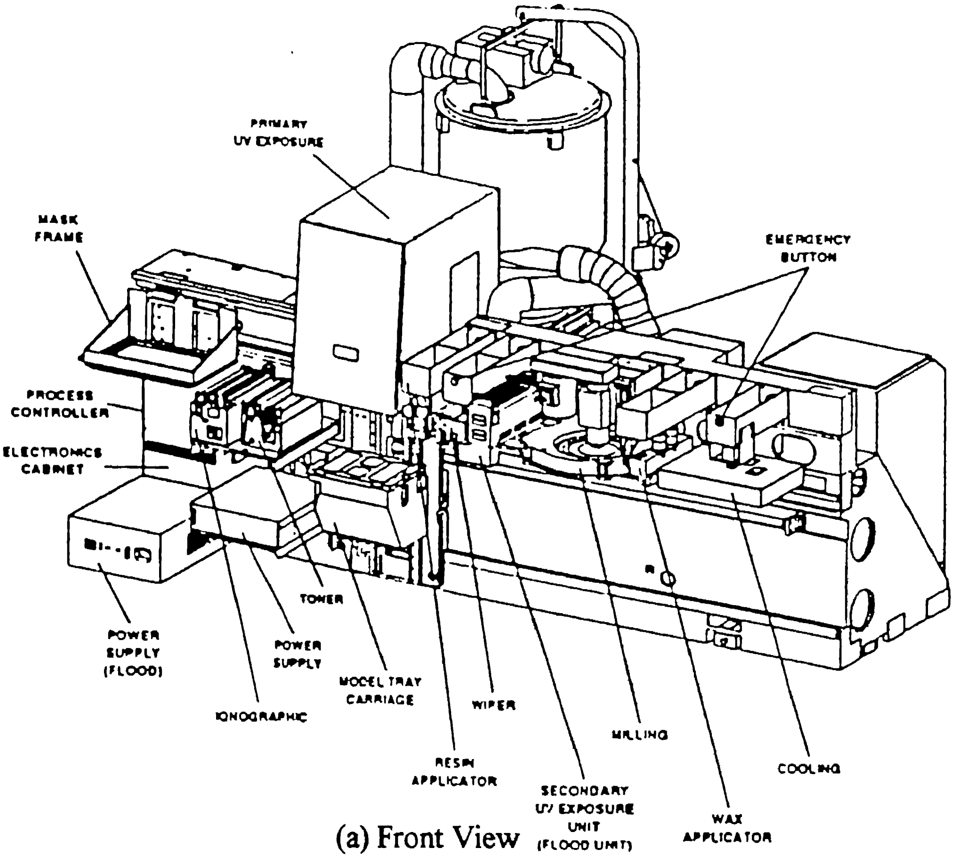
Mylar Sheet. It as a transparent sheet on which the mask generated. The sheet stores electrostatic charge that attracts toner to generate the mask. This sheet of non-conducting plastic material is glued over the Metal-Coated Glass.

Metal –Coated Glass. It stabilizes the position of the electrostatic charge placed on the Mylar Sheet. This glass plate is coated with a conducting metallic film that is grounded. Coulomb forces between the metal film and the electrostatic charge stabilize the charge on the sheet.

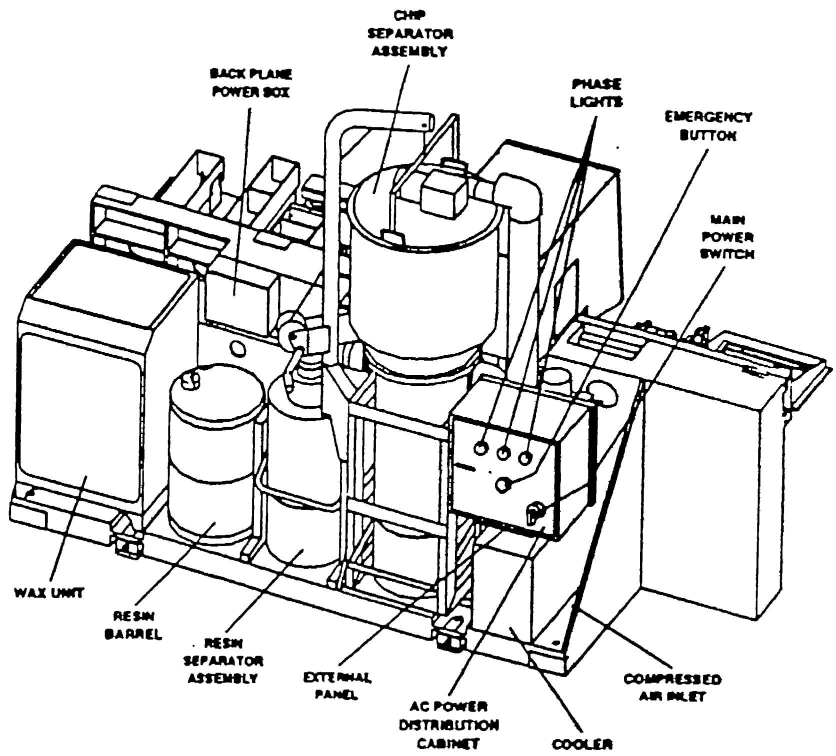
Mask Frame. It moves and provides a level support for the Metal-Coated Glass and Mylar Sheet.

3)Ionographic Unit.

The Ionographic Unit neutralizes charges from the Mask Unit and creates an electrostatic image of the next layer on the Mylar Sheet. The major components are:



(a) Front View



(b) Back View

Fig.2.8: Solider 4600 System Front view and Back view

Erase Rod. It discharges the residual charge from the Mylar sheet. There are six axial wires on the rod. The wire positioned at 12 o'clock is active. The other five are spares.

Ion Cartridge. It jets ions into the Mylar sheet creating an electrostatic image of the next layer. The upper surface of the cartridge contains holes(256 angled rows of 16 holes each) that are fired in a pattern determined by the information received from the Process Controller.

Air Shield. It maintains a flow of air across the top of the Ion cartridge to protect it from contamination by toner powder. Compressed air flows into the shield, exits through the holes on the side, and flows across the upper surface of the cartridge.

Handle Sets. Overlapping handles that secure the Ion Cartridge in position. The lower one raises the cartridge to the correct height and locks it there. The upper one pushes the electrical boards against the contact pads of the Ion Cartridge.

4)Toner Unit.

The toner unit removes the previous mask and develops the next one. After primary exposure, the toner unit wipes toner from the Mylar Sheet thereby erasing the previous mask. After the next electrostatic image is formed on the sheet, toner from the Developer Unit is attracted to the charge areas, creating the mask for the next layer. It contains the following units.

Cleaning Blade. It erases the mask. Pneumatic pressure pushes the urethane rubber blade against the Mylar Sheet to scrape away the toner. The slow, steady movement of the blade prevents toner from contaminating other units.

Brush Roller. It rotates against the cleaning blade and cleans it when the blade is at rest.

Toner. It is the black powder mixed with magnetic particles that is attracted to areas of electrostatic charge on the Mylar Sheet.

Develop Roller. It is a rotating magnetic roller on which toner collects before behind attracted to the Mylar Sheet.

Model Production Cycle functional units

The various functional units, which participate in the Model Building Cycle are discussed hereunder.

1) Resin unit.

The resin unit covers the entire upper surface of the Model Tray with a uniform layer of liquid resin. The thickness is adjusted to 160-220 μm in height. The Resin unit :

- Pumps liquid resin from a storage barrel into the applicator
- Heats the resin for achieving optimum viscosity
- Lowers the resin applicator 2mm downward to the spreading height, and after spreading, lifts it back to idle height
- Pushes a volume of liquid resin through a slit and lays it like a blanket onto the upper surface of Model Tray.

2) Primary Exposure unit.

The primary UV unit selectively polymerizes the resin layer by exposing it to UV radiation through the mask. The exposed portions of the reisn are polymerized and remain on the workpiece when the unpolymerized liquid resin is removed by the wiping unit.

UV lamp. A quartz bulb is located in a reflector cavity which receives energy from a magnetron that generates microwave energy at 2450 MHz. The microwaves heat the bulb to create a radiation-emitting plasma. The spectral characteristics of the emitted radiation are controlled by chemical additives in the bulb. Protective screens prevent microwave radiation from escaping to the surrounding area. An igniter bulb is included in the system to ensure proper starting of the lamp bulb.

Shutter. It is a pneumatically operated system to control the exposure time of the resin to UV radiation.

Magnetron cooling interlock. It shuts down the system if magnetron heats up beyond operating temperature. When the magnetron cools down, the system resets automatically and operation can resume.

3) Wiping unit.

The wiping unit removes liquid resin from the top surface of the model. The liquid resin left represents 'spaces' in the model layer. The major units of the wiping unit are -

Air blower and slit. It produces a thin, powerful stream of air to lift liquid from the surface and to roll the wave of liquid resin towards the collector blade and slit. An air pressure gauge and regulator are used to maintain the correct air supply for the blower.

Collector blade and suction slit. It guides the rolling wave of liquid resin into the opening of the slit. The vacuum pressure present at the slit opening extracts the liquid resin from the blade and carries the resin into the resin separator.

Resin separator. It separates the liquid resin from the air stream to collect it for reuse and to prevent it from reaching the vacuum unit.

4) Wax Unit.

After the liquid resin remaining from the primary exposure is wiped away, the wax unit spreads a layer of liquid wax approximately 300 μm thick across the entire surface of the model tray. The wax covers hardened resin and fills in void to support the structure of the models during model building cycle. The wax unit

- Melts blocks of wax in the melter
- Stores melted wax and continuously stirs it in a conditioning tank
- Heats melted wax throughout the unit.
- Pumps melted wax from the conditioning tank into the applicator
- Lowers the applicator 2 mm downward to the spreading height, and after spreading, lifts it back to idle height
- Pushes a volume of melted wax through a slit and spreads it like a blanket onto the upper surface of model tray.

5) Cooling unit.

The cooling unit rapidly cools and solidifies the wax layer. The cooling occurs by physical contact between the wax layer and the cooling plate. The cooling sequence is as follows

- After a liquid wax layer is spread, the Model Tray moves to underneath the cooling plate.
- The Model Tray it is positioned under the cooling plate.
- The piston moves the Inner Box in the Cooling Plate downwards and makes it in touch with the outer box, and that chills the cooling plate.
- Both boxes move down and press together on the wax layer. The cooling plate chilled by the cold transfer plate, solidifies the wax.

6) Milling unit.

The milling unit mills the last layer of solid wax and hardened resin to a finished thickness of 150 ± μm. As the milling proceeds, the milling unit sucks chips and dust out of the milling area for disposal.

7) Vacuum unit.

The vacuum unit is used by the wiper and milling unit. The vacuum generator generates a strong vacuum using an electric motor which drives a large turbine. The vacuum manifold switches the vacuum source to either the resin separator or the chip separator line.

2.6 Job Production Procedure In Solider 4600

The total procedure for producing a job can be divided into three distinct areas. They are Pre-production, Production and Post-production. In each area the steps, which are required to follow are explained below.

2.6.1 Pre-production

Pre-production stage can be divided into two separate parts, the first one is related to Data Front End (DFE) and the other one is related to Model Production Machine (MPM). These two parts of the Pre-production can be done simultaneously for any job.

Pre-production on DFE side

1. The input for the machine is a 3-D CAD file in any format. If the input file available is in format other than STL (Binary/ASCII) or CFL, it should be converted to CFL format using translators available with the DFE software before opening the file in the Reception.

2. Open the file in the Reception and convert the file format, which is either in STL or CFL , into SOLI format. This is, because, the other applications of the DFE accepts only files with SOLI format.
3. Open the SOLI file in the Academy application of DFE and check whether there are any flaws. If flaws exist, repair the file using the tools available in the Academy.
4. Once it is sure that, there are no flaws, open the SOLI file in the Show application of DFE. In Show application, the size of the object can be changed if required. In this application, we can retrieve as many files as we required, for producing all of them in a single run. The nesting of the parts is the most important and critical of the whole process. The nesting of the parts should be done in such a way that the total thickness of the run should be as low as possible. While nesting the parts, it should be seen that all parts of the run should come into the volume indicated in the Show by a cubic box.
5. Once nesting is over, consolidate all parts of the run by creating a SHOW file. Once SHOW file has been created, create consolidated SOLI file for the same.
6. Once consolidated SOLI file has been created, the next step is opening the file in the Production application of the DFE software. In the Production, we can check whether there is any interference between the parts of the run. If some interference was found, we should go back to the Show application make necessary modifications in nesting and consolidate the file again.
7. Once it was found that there was no interference, submit the job to MPM in the Production application.

Pre-production on MPM side

1. Check the resin drum to see if there is sufficient supply of resin. Make sure the supply is sufficient for the pending job.
2. Open the Wax-Tank cover and visually check wax level. If level is less than half, add wax blocks to melter.
3. Check the main compressed air supply. Air pressure should be 7-8 bar.
4. Check the water level in water cooling unit and switch on power. If the system is in Active mode the indicator light should glow.
5. Visually inspect the chip collector and make sure that it is empty.

6. Visually inspect the residual Resin Collector and make sure that there is enough room for additional spent resin. If possible, the Resin Collector should be emptied before starting a new job.
7. Make sure that the Vacuum Generator main switch and Standby button located on the front panel of the Vacuum Generator is on.
8. Place a tray below Wax Applicator and produce a wax curtain by pressing the Wax Unit diagnostic button. If the first curtain is not uniform, try two or three times to get a good curtain. Even after pressing the diagnostic button three times if the curtain is not good, open wax filter and Applicator Blade and clean them with hot water.
9. Turn off Milling Head power switch located on the front of the unit and visually inspect the Chip Collector hood for blockage. Clean it in case of any blockage.
10. Clean wiping unit with alcohol and make sure that the air slit is unobstructed.
11. The flow of resin (curtain) from the applicator should inspected for the correct curtain, it can be produced when air bubbles are absent and the Resin Slit is clean. To check this, produce a resin curtain by pressing diagnostic button located underside of the Resin Applicator. Check the rate of pressure rise on the resin spread pressure gauge when the curtain is being produced. The pressure should rise quickly and stabilize at operating value. If, the Resin Applicator is unable to produce a uniform curtain even after 2-4 attempts, bleed air from the resin system.
12. Make sure that Ion-cartridge in the Mask Generator is in place. Visually inspect the Cartridge surface, if necessary clean it carefully with Vacuum Cleaner. Gently clean Glass Plate of the Mask Frame with soft non-abrasive paper towel. Now, check the Mask Generator by producing standard sample masks from disk.
13. Check parameter settings for the various units from Update command against the prescribed values.
14. Examine the PVC workpiece base and make sure that it is clean and free from defects. If necessary, mill down the PVC workpiece base to a smooth and even surface and record the Z-axis at this instant as ΓAG-1. After this put some base resin layers over the PVC slab to complete the preparation of the workpiece base.

2.6.2 Model Production

After the workpiece has been prepared and base resin layer produced, model building can be started. The basic steps, which are required to follow, are given hereunder.

1. Before starting the new model batch set Next Frame value to 1. By this, the current layer value will automatically reset to 0.
2. After the Next Frame value has been set to 1 using Modify command, record the resin layer height as TAG-2.
3. If you have changed the first exposure time, then reset it to the model building value.
4. In Update parameter list, set the work station or file source parameter.
5. If mask data is to be sent from the Data Front End, request layer files from DFE operator. When DFE operator confirms that data is ready to send, model building can be started.

2.6.3 Post-production

In this stage, removal of the wax from the job, which was used as supporting structure while job was being built, is done. Besides this, since the surface-finish of the parts are not good after removal of wax, some surface-finishing method should be used.

1 Once job production process is completed on the MPM, bring down the Model Table in the Z-axis to facilitate removal of the job.

2 Remove the job with Model Tray from the Model Table and carry it to the cleaning room for separating the job from the Model Tray.

3 For separating the job from Model Tray, first chip out the fence from all the sides to make the job free.

4 After separating the job from the Model Tray, Put the whole block in a tub, which contains citric acid solution maintained at 40 degrees temperature.

5 Keep the block in the citric acid solution until all the wax has been desolved. Once all the wax been desolved parts will come out.

6 Take out the parts from the citric acid solution, dry and give them surface finish using emery paper.

6.7 SOLIDER Materials

Solider resins are Acrylic based photopolymers specially formulated for use in the Solider Model Production Process. The resins are non-volatile and insoluble in water. Polymerization may be initiated by heat, oxidizing agents, or exposure to UV radiation. The resins are supplied with a polymerization inhibitor which have limited lifetime of six months. There are two kind of resins namely G-5601 and X-607 for making the models. The wind tunnel model (Agard-B) used in the present work was made of G-5601. The properties of the material are:

Liquid resin

1) Density	@ 25°C	1080 kg/m3
2) Viscosity	@ 20° C	6500 m Pa s
	@ 30° C	2300 m Pa s
	@ 40° C	900 m Pa s

Cured Resin

1) Tensile strength	@25° C, 50% RH	30 Mpa
2)Elongation	@ 25° C, 50% RH	15%

Chapter 3

MODEL DESIGN AND DEVELOPMENT

The inputs for the model design and development are model drawing, details of wind tunnel and balance & material properties of model material. The various steps in this process are explained below in the order of their importance. In the first section, the technical details required for the model generation are given. Second section includes finding critical sections in the model and checking the material suitability before going for actual model generation. The third section contains fixation of the scale factor for the model according to the various technical constraints. The fourth section covers various calculations required before going for solid modeling part of the model. The model, which was selected for aerodynamic wind tunnel testing, was Agard-B, which was obtained from National Aeronautical Laboratories (NAL), Bangalore. The fifth section covers procedure for solid modeling of the model using Pro-Engineer package. After creating CAD model for Agard-B wind tunnel model, the model production procedure for making RP model, was explained in the second chapter of this report.

3.1 Technical Details Required for Aircraft Model Generation

The basic requirement for modeling any part is a drawing. Besides, if it is required to go for any testing of the model, the size and weight to be chosen for the model depend upon the instrumentation, to be used for the testing purpose. So before going for actual modeling, the details of the wind tunnel and balance are required. Lastly, for model fabrication, the size of the model depends upon the RP machine working volume and the strength of the model depends on the modeling material that can be used in the machine.

Drawing for Agard-B model

The drawing for wind tunnel model Agard-B is shown in Fig.3.1 with various details.

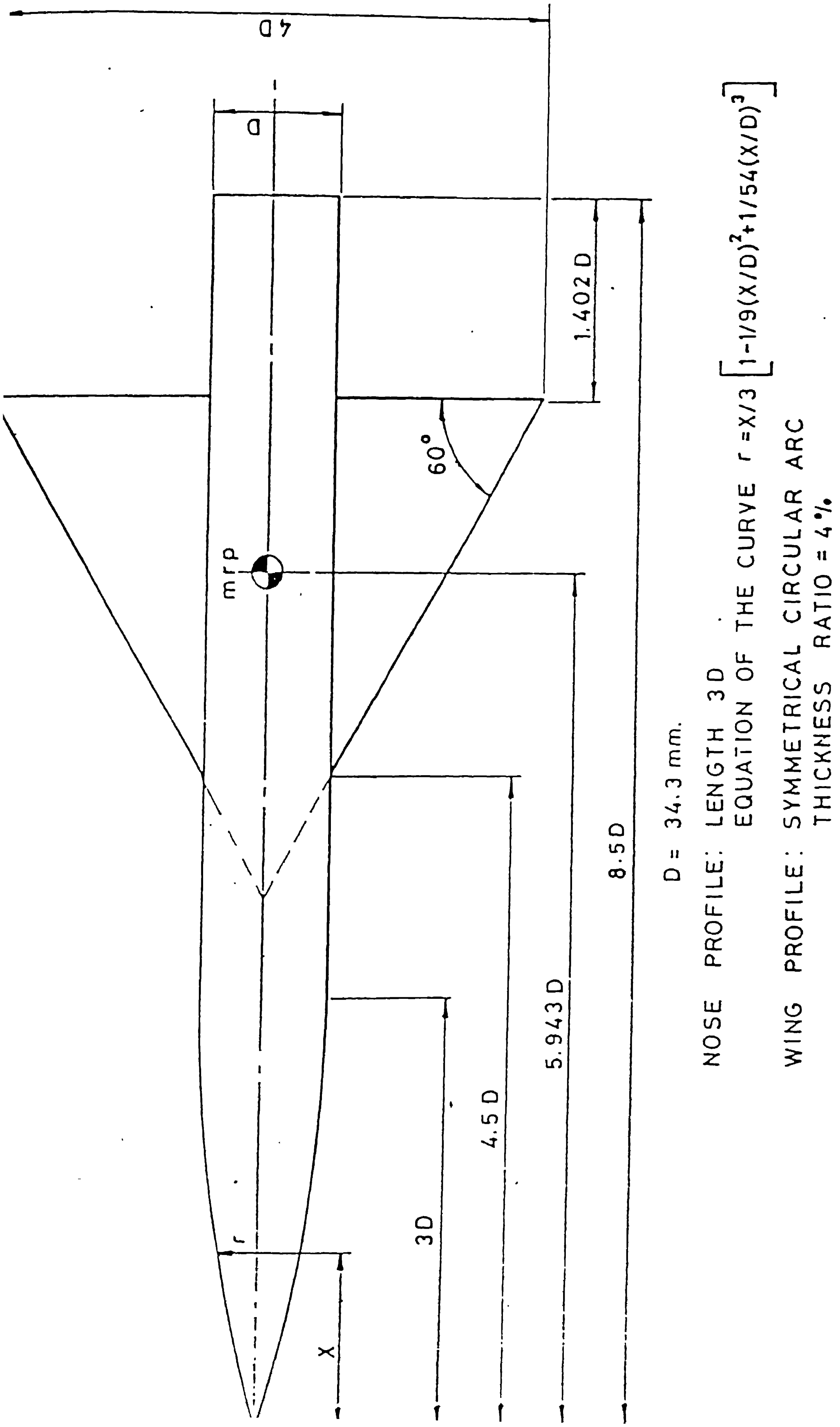


FIG.3.1 AGARD-B MODEL

Details of the wind tunnel

Speed range	62 – 115 fps
Reynolds number range per feet	0.35 to 0.7 x 10^6
Dynamic Pressure	16 pounds / feet^2
Total temperature	570^0 R.
Size	3 x 2 x 5 ½ feet.
Cont. Ratio	6
Turbulace Level	1%

Details of Balance

The balance, which was used for the experiment, was three component external balance. The maximum load ratings and minimum size of the model that can be fixed are given below.

Lift	+/- 120 N
Drag	+/- 60 N
Pinch	+/- 2.5 N-m
Length	14 cm
Width	6 cm

Details of the RP machine

Machine working volume

Length	20 inch.
Width	14 inch.
Height	20 inch.

G-5601 material properties

Tensile strength	27 Mpa.
Heat Deflection Temperature	40^0.

3.2 Checking RP Model Material Suitability

Before going for actual solid modeling and subsequent experimental part, it should be worth while to check, whether the model can sustain the maximum loads, which will be coming during testing. For this checking, it is required to find out the most critical sections for the model. From the geometry of the model, it can be said

that the wing root section is the most vulnerable for any failure to occur. So in this root section of the wing it is required to check that the bending stresses, which will be coming when the maximum load is being applied, are within the permissible limits according to the material strength of the RP model. To check this, basic calculations have been done using the experimental data available for the metal model and the properties of the RP model material.

The cross-section of the wing at the root section with various dimensions and wing plan view are shown in Fig.3.2. For calculating bending stresses, it is required to calculate the moment of inertia of wing section at the root of the wing. The cross-section can be approximated with a rectangular section for calculating moment of inertia, since these calculations are only for preliminary checking.

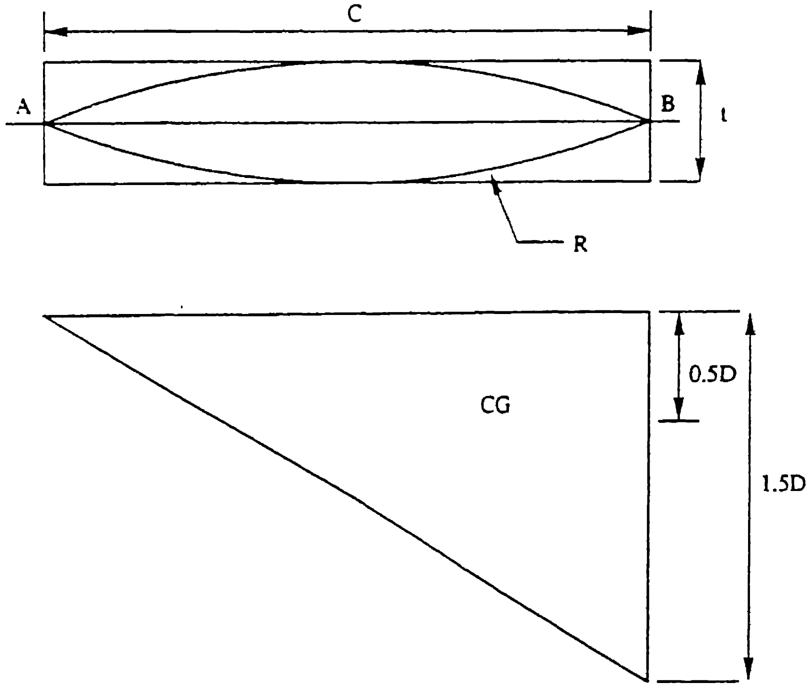


Fig.3.2: Wing Cross-section and Plan-view

From the drawing, the values of C, R and t at the root section of the wing are given below (the calculations to finding them are shown in the fourth section of this chapter).

C = 89.11 mm.

R = 557.83 mm.

t = 3.56 mm.

From these values the moment of inertia of the section about the axis AB can be calculated using the following formulae.

$$I = C\,t^3/12 = 335\ \text{mm}^3.$$

Values of coefficients C_N, C_D are available from the experimental data of the metal model and are shown in Fig.3.3. For calculating lift and drag forces acting on a single wing, values of C_N, C_D can be read from the graphs. At an angle of attack of 15^0, the values of coefficients are,

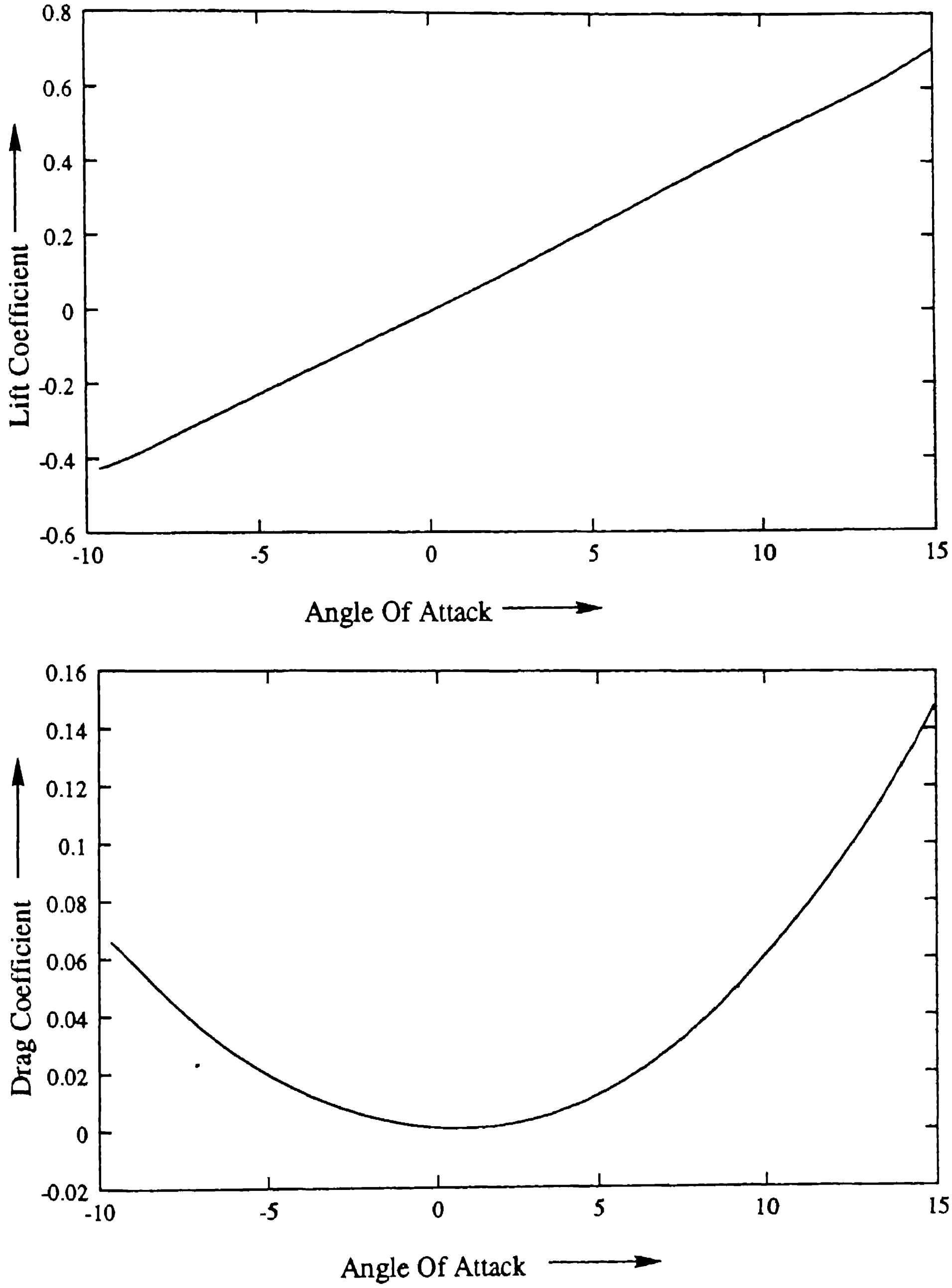


Fig.3.3: Coefficient Graphs for Metal Model

$$C_N = 0.7$$

$$C_D = 0.15$$

From the wing plan view, the area of a single wing (S) is equal to 2292.39 mm^2 (for D=34.3 mm). And the distance of the centroid of the wing from the root section is equal to 17.15 mm(1.5/3 D).

The dynamic pressure (q) from the wind tunnel specification is equal to 767.96 N/m^2.

From the above-calculated data lift and drag forces can be calculated using following formulas.

$$N = C_N\, S\, q = 1.23 \text{ N}$$

$$D = C_D\, S\, q = 0.26 \text{ N}$$

From these two force components, the resultant force (R), which is acting perpendicular to wing surface is equal to 1.581 N.

From centroidal distance and the resultant force, the bending moment (M) about the wing root section is equal to 27.1 N-mm.

Using bending equation, the maximum bending stress (f), which will be coming to the wing root section can be calculated from the below given formulae.

$$M / I = 2\, f / t$$

From this, the value of maximum bending stress is equal to 0.144 N/ mm^2.

From the list of RP material properties, the tensile strength of the material is given as 27 MPa. Since, there is a large difference between the maximum bending stress induced and material tensile strength, it can be said that RP material used for model making is quite suitable.

3.3 Scale Factor Fixation

The scale factor to be used for model generation depends upon three considerations.

1. The blockage ratio should be below 6%.
2. Size of the model should be such that, it can be fixed on the balance, which is used to take measurements of lift, drag and pitch.
3. The size of the model has been fixed from above two considerations should be such that, it can be fabricated on the RP machine available.

This is explained further in the following section.

Blockage Ratio Consideration

For calculating blockage ratio, it is required to know the model plan area and maximum angle of attack, which is going to be used in actual experimentation. The plan view of the model is shown in the Fig.3.4.

The model plan area in terms of diameter of fuselage is given below.

Plan Area $= \frac{1}{2} \times 3D \times D + 5.5D \times D + \frac{1}{2} \times 2.598D \times 1.5D$

$= 12.397 \times D^2$

The maximum angle of attack, Which is going to be used in the experiment, will be 20^0. So, when the model is fixed in the wind tunnel section at 20^0 angle with the wind velocity, then the total projected area can be calculated as below from Fig.3.5.

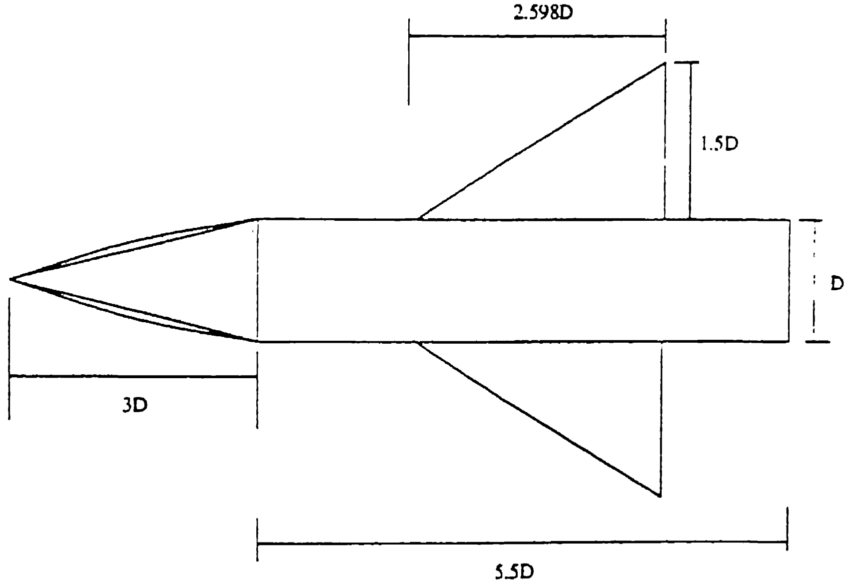


Fig.3.4: Model Plan-view

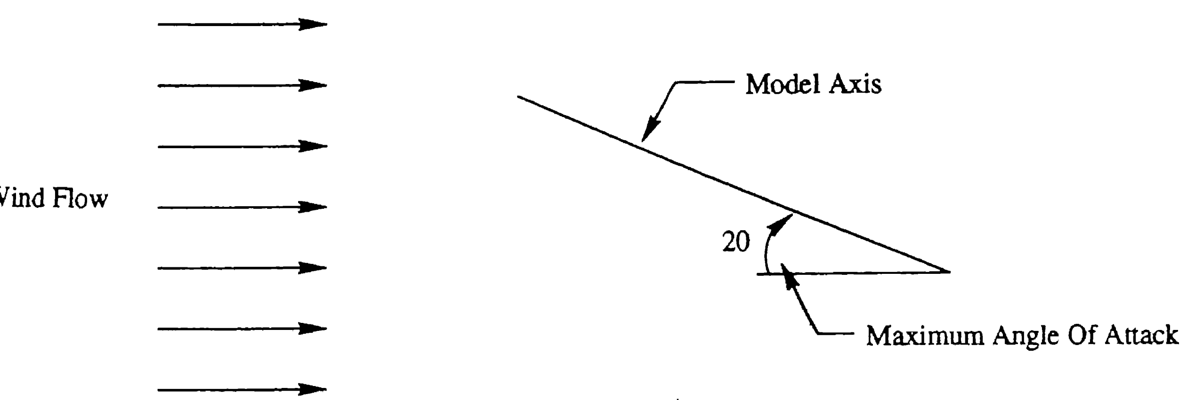


Fig.3.5: Model at maximum Angle of Attack

Projected area = Sin 20 x Plan Area of the model

= Sin 20 x 12.397 x D^2

From the wind tunnel test section dimensions, cross-sectional area of the tunnel = 3 x 2 = 6 $feet^2$ = 566231 mm^2

Blockage Ratio = Area that is blocked by the model in the wind flow/ total cross-sectional area of wind tunnel test section.

= 4.24 x D^2 / 5666231

For the present wind tunnel the maximum permissible blockage ratio is 6%. So, it has to be calculated, at the maximum blockage ratio value, what could be the maximum allowable diameter for the fuselage to decide the permissible range. Therefore,

$$0.06 = 4.24 \times D^2 / 566231$$

From this, the maximum permissible value for D has been decided as 89.5 mm. So for the model, the fuselage diameter should be below 89.5 mm to test in the present wind tunnel.

Model Mounting Consideration

The model is going to take support from the balance using three struts during testing as shown in Fig.3.6. The minimum distance, which can be used between the front two struts, is 6 cm. So, to fix the model properly between these two struts, the model fuselage diameter should be approximately equal to 6 cm. In the present model, when we take a scale factor of 1.5 then the fuselage diameter is coming approximately to 6 cm for proper mounting.

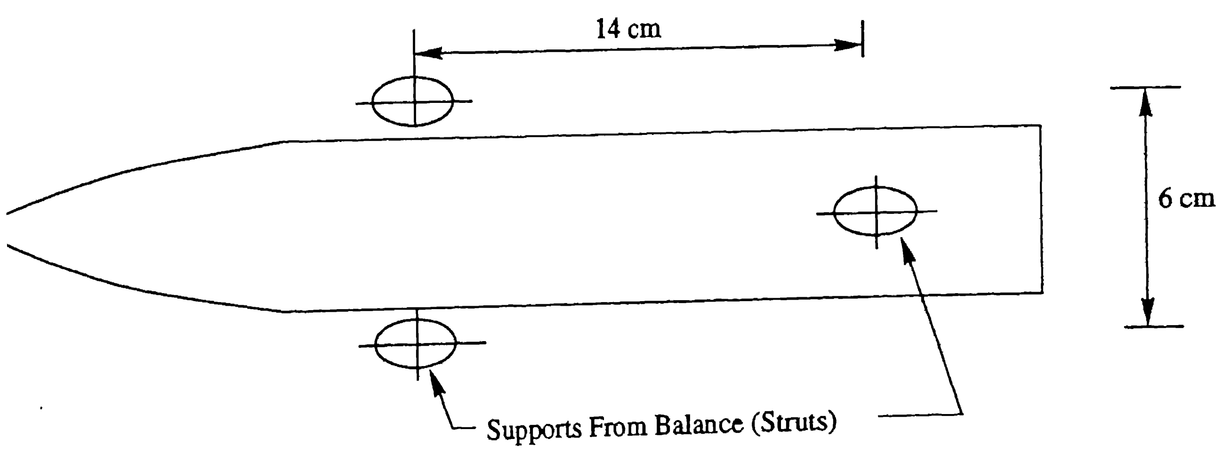


Fig.3.6: Model with Strut positions

RP machine working volume consideration

The scale factor for the model, which has been fixed according to the previous two considerations, should be such that it can be fabricated from the machine. From the RP machine working volume consideration, the maximum length of the model that can be fabricated from the machine is 508 mm. For the present model, the length required will be 583.1 mm when the scale factor is 2, which is beyond the machine capacity. But, when the scale factor is 1.5, the total length of the model is coming within the permissible limits from the machine working volume consideration.

From these three considerations, scale factor for the model creation has been decided as 1.5.

3.4 Pre-calculations Required Before Actual Solid Modeling

It is not always possible to create a 3-D model, directly from the dimensions available in the drawing. Before going for solid modeling some preliminary calculations are needed generally. In the present model, calculations are required for the nose and the wing part of the model.

Nose geometry

For creating the nose profile, the equation was given in x and r coordinates in the drawing. But, the modeling package requires parametric equations for creation of the nose profile most accurately. So conversion of the given equation to parametric equations is required and it has been evolved as follows.

From the drawing, given equation for nose is,

$$r = x/3\ [1 - 1/9\ (x/D)^2 + 1/54\ (x/D)^3]$$

In this equation x value varies from 0 to 3D. Taking u as a parameter varying from 0 to 1, the parametric equations for x and r are,

$$x = 3D\,u$$

$$r = D\,u\,[1 - u^2 + \tfrac{1}{2} u^3]$$

Wing geometry

For getting wing geometry precisely the option, which is available in Pro-Engineer is blending. For blending, with better control over the surface profile, three parallel cross-sections are required. In the drawing, it was given that the wing profile is

a symmetrical circular arc with thickness ratio 4%. From this given condition, the details for blending of three cross-sections can be evolved from the geometry shown in Fig.3.7. .

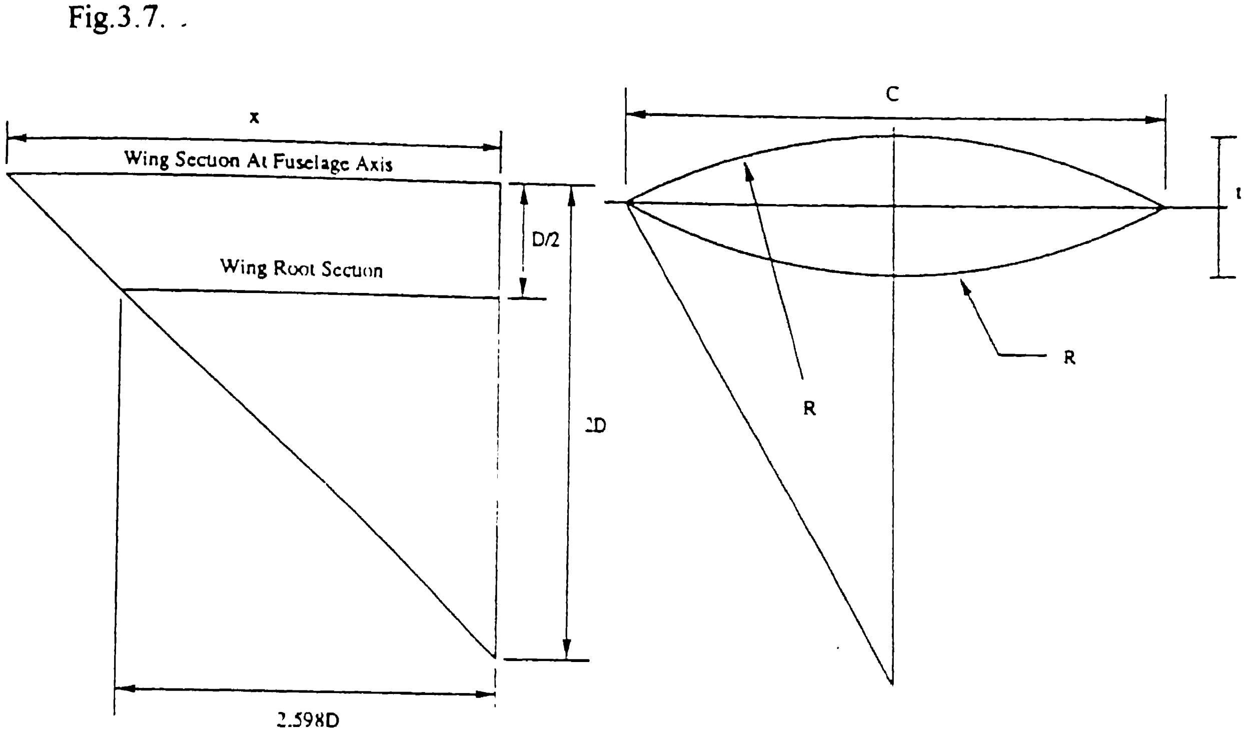


Fig.3.7: Wing Plan and Sectional views

From the given thickness ratio 4%, t / C = 0.04.

It is now required to find the radius of curvatures for the three curves at the three different cross-sections, which are going to be used for blending. From the geometry of the wing cross-section,

$$R^2 = (C/2)^2 + (R-t/2)^2$$

$$C^2/4 + t^2/4 = Rt.$$

$$R = (C^2+t^2)/ 4t$$

For finding the radius of curvature of the wing profile it is required to know the chordal length and thickness at these sections. From plan view of the wing, chord length at the root of the wing is known. Hence, the chord lengths at the other two sections can be calculated using similarity principle for triangles.

The chord length, thickness and radius of curvature are calculated at section 1 as follows.

$$C_1/ 2.598D = 2D/1.5D \text{ (from wing plan view)}$$

$C_1 = 118.82$ mm.

From the thickness ratio 4%, the thickness at the section 1 can be calculated as follows.

$C_1/t_1 = 0.04$

$t_1 = C_1 / 0.04 = 4.753$ mm.

From the previously evolved equation for the radius of curvature for wing profile, the radius of curvature at section 1,

$R_1 = 743.78$ mm.

The chord length, thickness and radius of curvature at section 2 can be calculated as before and their values are,

$C_2 = 89.11$ mm.

$t_2 = 3.56$ mm.

$R_2 = 557.83$ mm.

Similarly, the values of these parameters at section 3, which is at 1.99D from the axis of the fuselage are,

$C_3 = 1.04$ mm.

$t_3 = 0.042$ mm.

$R_3 = 6.51$ mm.

3.5 Solid Modeling Procedure

For CAD model creation, the package which was used in the present work was Pro-Engineer. Using this package the model has been created in three stages. In the first stage part models were created for the fuselage and the wing separately. In the second stage, these two parts were assembled in assembly mode. In the third stage, STL file was created for the model for obtaining an input file to RP machine.

Creation of Part Files

1. Open Pro-Engineer package and enter part mode. Then it will ask for file name, which is required to create. Enter the part name for fuselage creation.
2. From different options available from the *part mode* menu like solid, surface, datum etc., select datum for creation of datum planes, used as reference planes for the part which is going to be created.

3. After creating datum planes, select solid option from the *part mode* menu. Then Pro-Engineer prompts for selecting protrusion from the *solid* menu. After selecting protrusion, it will ask for an option from the *protrusion* menu, contains options like extrusion, revolve, blend, sweep etc. Among these select revolve and press done.
4. In the next step Pro-Engineer asks for sketching and reference planes for drawing and dimensioning the section of the model from the three datum planes, which were created before. So, from these three planes select one datum plane as sketching plane and second one as reference plane.
5. After selecting sketching and reference planes, it displays sketching plane for drawing the cross-section for the model. On sketching plane draw the half section of the fuselage using various options available in the *sketch* menu and dimensioning the section. Regenerate the section to find out any extra or under dimensioning for the section. If the section regenerates with out any error select done from the *solid* menu.
6. In the next step Pro-Engineer asks for, at what angle the section will be rotated about the centerline. For completing the part generation process, select 360 degrees and press preview button.
7. After getting the part with all requirements, from the *file* menu select save to store the part in the hard disk.
8. For creating the wing, the steps which are required are similar to the fuselage generation, except, instead of selecting revolve from the *protrusion* menu, it is required to select blend option.
9. After selecting blend, to generate the part it is needed to be created three sections of the wing on three sketching planes. For this, after completion of the sketching on one plane select section tools from the *solid* menu and select toggle from the *section tools* menu. At the end of the third section, select done from the *solid* menu after all the sections are regenerated successfully. Preview the part and save it.

Creation of Assembly File

1. After creation of two parts, which are fuselage and wing select assembly mode from the *main* menu.
2. Pro-Engineer asks for the name of the assembly file, which is going to be created. Enter the name of the assembly and select done.
3. After entering the name, select assemble from the *assembly* mode. Then, it asks for part, which is required to be assembled. Enter the part name for the fuselage to bring it to the assembly file.
4. In the next step, it again asks for the part, which is required to be assembled to the previously selected part. After giving the name of the part for the wing, the wing part will be opened in a corner window on the main window.
5. Now for constraining the part in the correct position with respect to the previously retrieved part, it displays options like merge, align, orient etc. Normally part requires three constraints to keep it in correct position. For this, select appropriate options from the *constraint* menu.
6. After placing the second part with respect to first one, select done to constrain the parts completely.
7. For completing assembly part save the file from the *file* menu.

Model of Agard-B after assembling in Pro-Engineer package is shown in Fig.3.8.

Fig.3.8: Agard-B Model from Pro-Engineer.

Creation of STL file

After creating assembly file for the model, STL file should be created for the same model, since RP machine software only accepts STL files.

1. Open assembly file for the model from the assembly mode.
2. After opening the file select interface option from the *assembly* mode menu. From the *interface* menu select export option, then it displays different file formats in which the file can be transferred. Select STL format among all.
3. In the next step it asks for the type of STL file, which is required to be created. There are two types of STL files, Binary and ASCII. Select Binary mode since RP machine accepts binary STL files.
4. Then it asks for the required chord length and corner angle for triangulation. These values decide the quality of the file. Enter appropriate values to get a good quality file.
5. After giving parametric values for triangulation, it asks for the file name for the STL file, which is going to be created. After giving the name, STL file will be created.

STL file was processed in DFE and the RP Model was produced using the Solider- 4600 system as explained in chapter 2. SGC-RP Model of Agard-B with some aerodynamic models produced from the RP machine are shown in Fig.3.9.

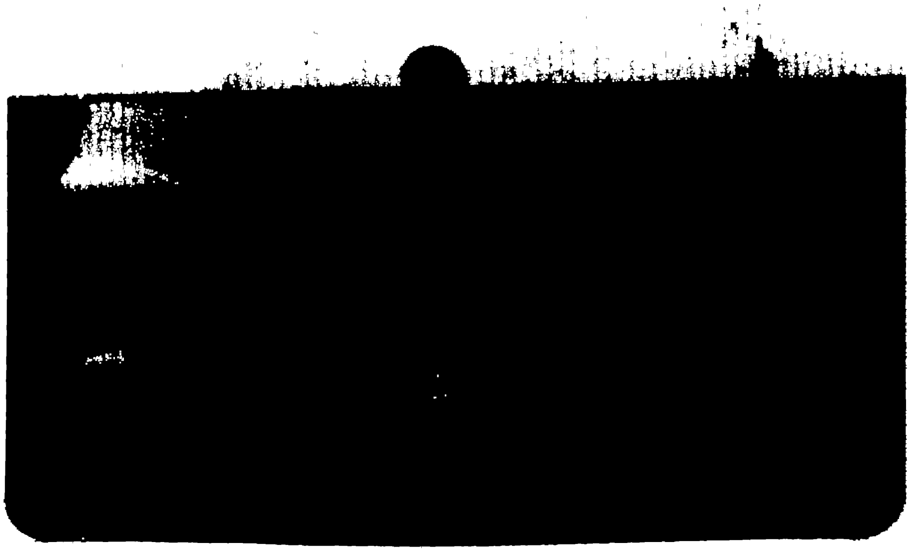


Fig.3.9: SGC-RP Models

Chapter 4

WIND TUNNEL AND FEM TESTING

4.1 Wind Tunnel Testing Procedure

The experimental set-up, which was used in the present experiment, is shown in Fig.4.1. Also shown is the schematic diagram of model mounting on the wind tunnel balance in Fig.4.2.

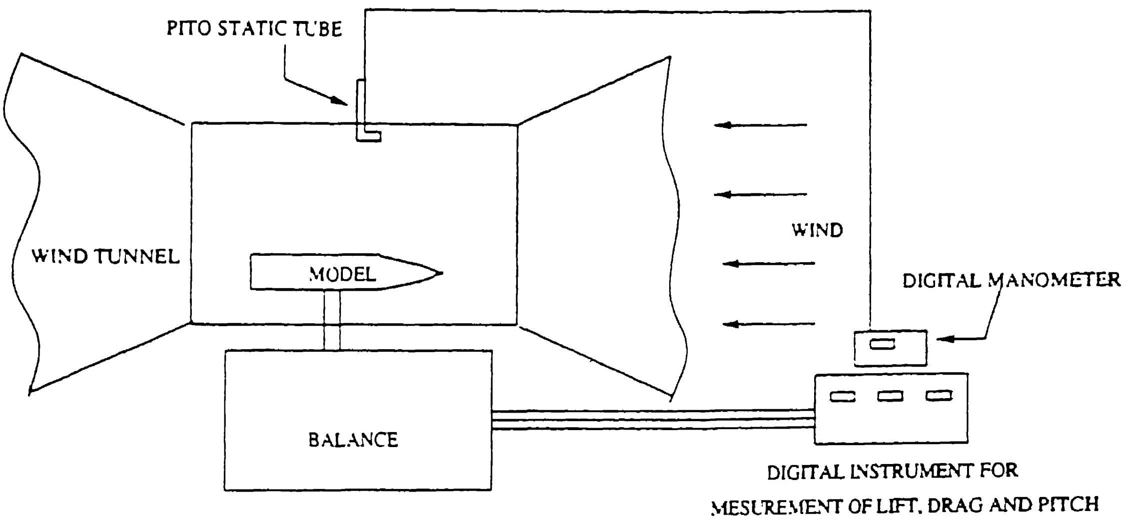


Fig.4.1: Experimental Set-up

The procedure required to be followed for experiment, is explained hereunder.

1. Switch on the power supply to the balance and allow approximately ten minutes for the system to warm up and the readings to stabilize. Meanwhile unlock the balance by screwing back the four clamp screws and removing the pitch-locking pin.
2. After the warming up period adjust all mechanical tare weights to give approximate readings on the digital displays.
3. Re-clamp the balance and insert the pitch-locking pin.
4. Mount the main struts to the strut platform at the desired distance apart.
5. Ensure that the tail arm angle is set to zero.

6. Slide the swivel joint of the tail strut onto the tail arm to the correct tail arm length and lightly lock in position with thumbscrew. Allow the tail strut to lean against the edge of the Tunnel floor or the balance earth frame for the moment.
7. Mount the model to the main struts using 3mm dowel pins through the spherical rod end bearings.

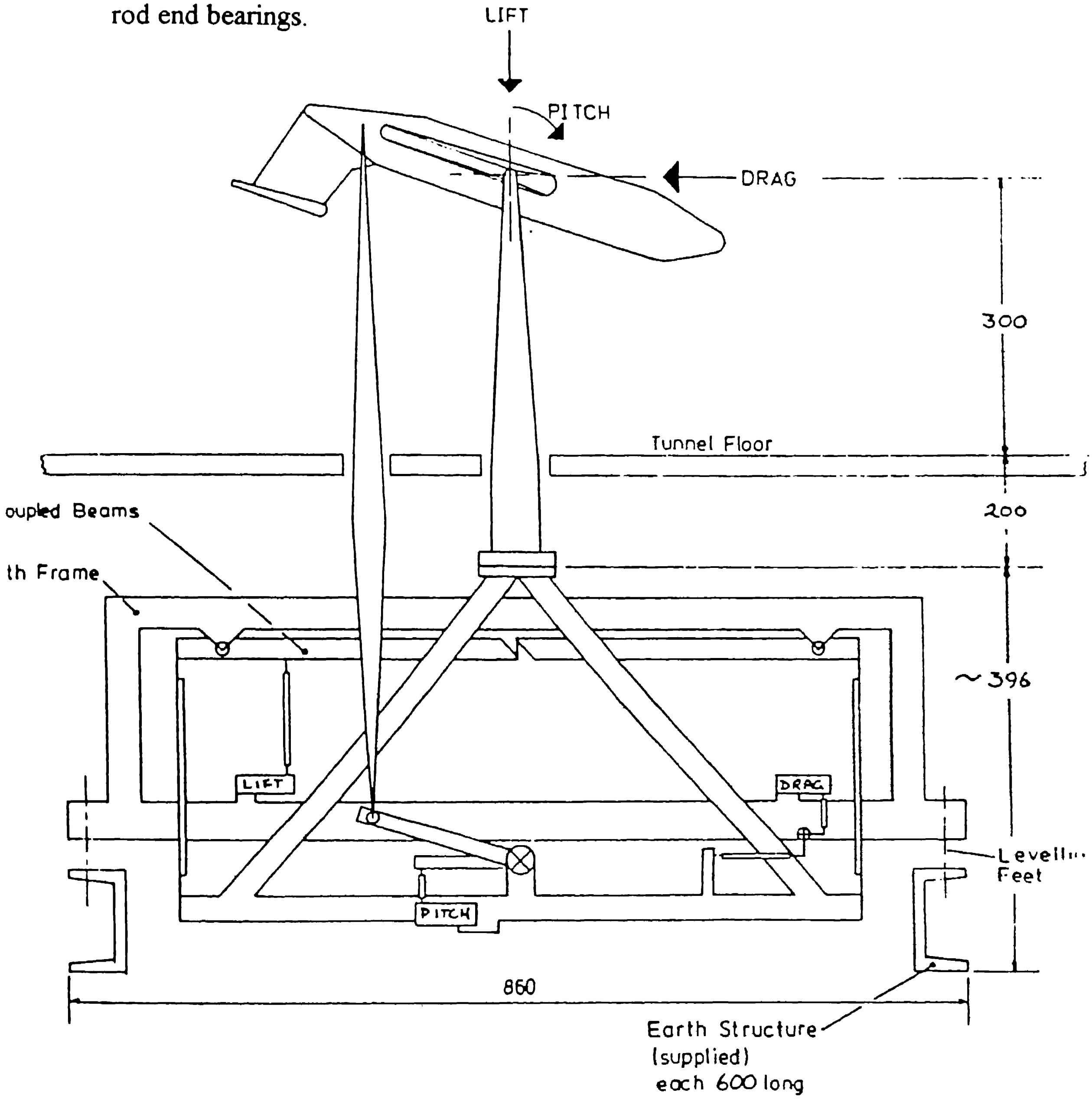


Fig.4.2: Schematic diagram of Balance

8. Next attach the tail strut to the model in similar fashion and adjust the tail strut to be truly vertical and at right angles to the tail arm.
9. At this stage unclamp the balance, remove the pitch-locking pin and re-adjust the tare weights to re-establish zero readings on the displays.

10. Check now, the horizontal axes of the model are as required and adjust if necessary by first locking the balance and adjusting the combined screw threads of the spherical bearings and their respective mounting studs.
11. Finally, with the balance unlocked, pitch-locking pin removed, all displays reading zero and the tail arm angle precisely at zero check that the model and its support system form a true right angled rectangle. Only then will the system behave as a true parallelogram when the tail arm angle is changed. The balance and model are now ready for wind-on testing.
12. After fixing the model on the balance, fix a static Pitot tube from the topside of the wind tunnel testing section and give necessary connections to digital manometer to measure the velocity of air during experiment.
13. Once all the set-up part is over, start the wind tunnel and adjust the speed of the wind by seeing its reading by the digital manometer to the required value.
14. Take the readings from the Drag, Lift and Pitch digital displays from the balance, when the wind speed has been stabilized at the required value.
15. Change the angle of attack of the model by the knob given on the balance to a value required and take subsequent values from the measurement displays.
16. According to the required range of angle of attack in which experiment will be conducted take sufficient steps required in between this range to get good experimental results. Keep the model at these angle of attack values consecutively and take the measurements from the balance for these values.
17. After finishing, switch off the wind tunnel and take the measurements of temperature and pressure at which the experiment was conducted to calculate density of the air later.

4.2 Results from Wind Tunnel Testing

Experiment was conducted on the RP wind tunnel model for a range of angle of attack from −10 to +14 in steps of 2. The measurements which were obtained from the balance at these angle of attack values were lift force and drag force. The pitch measurement was not working in the available balance. The time average readings, which were obtained from the experiment, are given in Table 4.1.

S.No	Angle Of Attack(α)	Lift Force(N) in Newton's	Drag Force(D) in Newton's
1	16	8.155	5.72
2	14	7.21	5.02
3	12	6.125	4.63
4	10	5.065	4.18
5	8	4.11	3.875
6	6	2.565	3.545
7	4	1.695	3.505
8	2	0.325	3.5
9	0	-0.505	3.355
10	-2	-0.98	3.35
11	-4	-2.145	3.395
12	-6	-3.475	3.5
14	-8	-4.925	3.625
15	-10	-5.8	3.725

Table 4.1: wind Tunnel test results

The speed of the wind at which the experiment was conducted is 33 m/sec. The Temperature and pressure values at the time of the experiment are 19.7^0 C and 72.4 cm of mercury.

For calculating the coefficients C_N, C_D, the formulas available are,

$$C_N = N/qS$$

$$C_D = D/qS$$

For calculating the values of coefficients, besides drag or lift force the other parameters, which are required are dynamic pressure (q) and model plan area (S). The calculations for dynamic pressure and mode plan area from the available values are as follows.

Dynamic pressure calculation

The Dynamic pressure (q) of air can be calculated by using the following formulae:

$$q = \frac{1}{2}\rho v^2$$

In this formulae, the velocity (v) of the wind during experiment is known, but the density value (ρ) of the air is required to be calculated from the available values of temperature and pressure of atmosphere at the time of experiment.

$$\rho = \frac{P}{RT}$$

$P = 72.4$ cm of mercury $= 0.965 \times 10^5$ N/ m^2

$T = 19.7^0C = 292.7^0K$

$R = 0.287$ kJ/Kg ^0K

$v = 33$ m/sec

From these values the dynamic pressure of air during experiment was calculated as 625.47 N/m^2.

Model plan area Calculation

From the plan view of the model available, the total area of the model can be divided as shown in Fig.4.3.

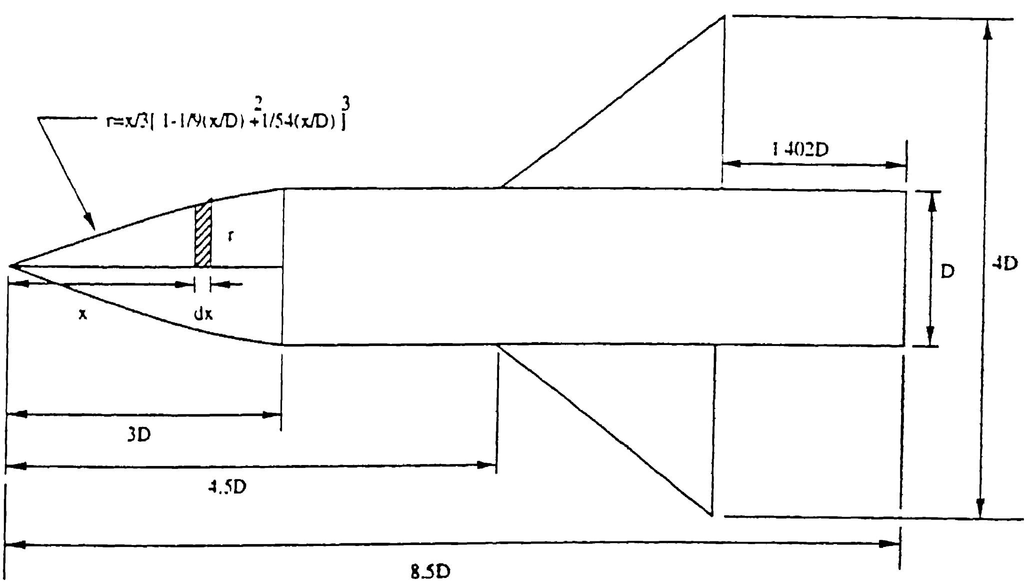


Fig.4.3: Model Plan-view for Area

Model plan area = 2 (half portion area of nose) + 2 (wing area) + fuselage body area

$$= 2\int_{0}^{3D} x/3[1-1/9(x/D)^2+1/54(x/D)^3]dx + 2(1/2 \text{ x } 3/2D \text{ x } 2.598D) + D \text{ x } 5.5D$$

$$= 21/10\, D^2 + 3.897\, D^2 + 5.5\, D^2$$

$$= 11.497\, D^2$$

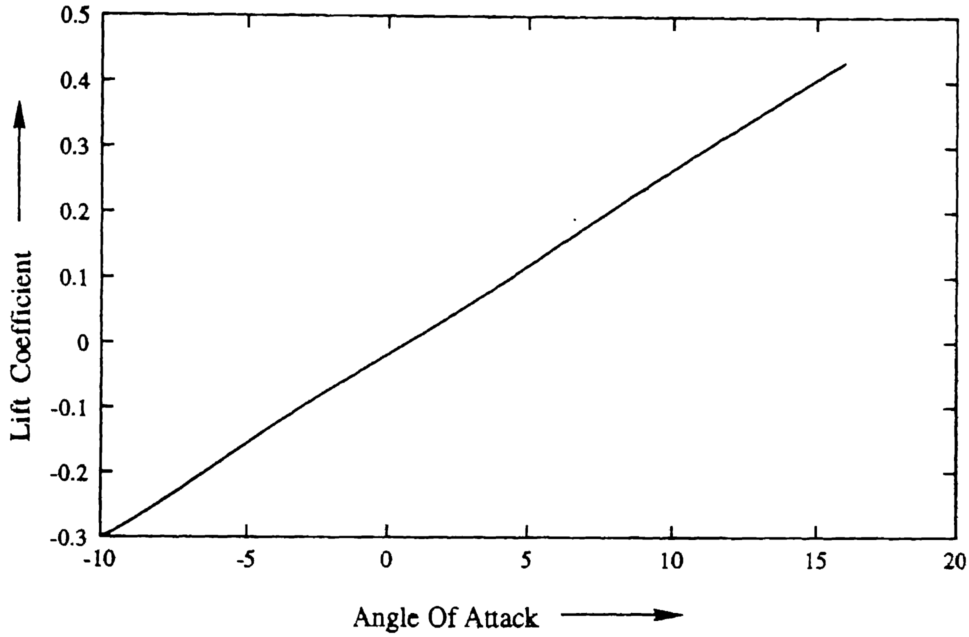
When we consider the model with 1.5 scale factor, then the D value will be 51.45 mm. For this value of D, the model plan area will be 30433.74 mm^2

Using the formulas for drag and lift coefficients, the above calculated values of dynamic pressure and model plan area, and from the experimental values of drag and lift forces, the values of drag and lift coefficients can be calculated. The calculated values of these coefficients are given in the following Table 4.2.

S.No	Angle Of Attack α	Lift Force(N) Newton's	Drag Force(D) Newton's	Coefficient Of Lift(C_N)	Coefficient Of Drag(C_D)
1	16	8.155	5.72	0.431	0.302
2	14	7.21	5.02	0.381	0.265
3	12	6.125	4.63	0.323	0.244
4	10	5.065	4.18	0.268	0.220
5	8	4.11	3.875	0.217	0.204
6	6	2.565	3.545	0.135	0.187
7	4	1.695	3.505	0.09	0.185
8	2	0.325	3.5	0.017	0.185
9	0	-0.505	3.355	-0.027	0.177
10	-2	-0.98	3.35	-0.052	0.177
11	-4	-2.145	3.395	-0.113	0.179
12	-6	-3.475	3.5	-0.183	0.185
13	-8	-4.925	3.625	-0.26	0.191
14	-10	-5.8	3.725	-0.3	0.196

Table 4.2: Coefficient values

From the available values of lift and drag coefficients at different angle of attacks, graphs are drawn between coefficients and angle of attack values and are shown in Fig.4.4.



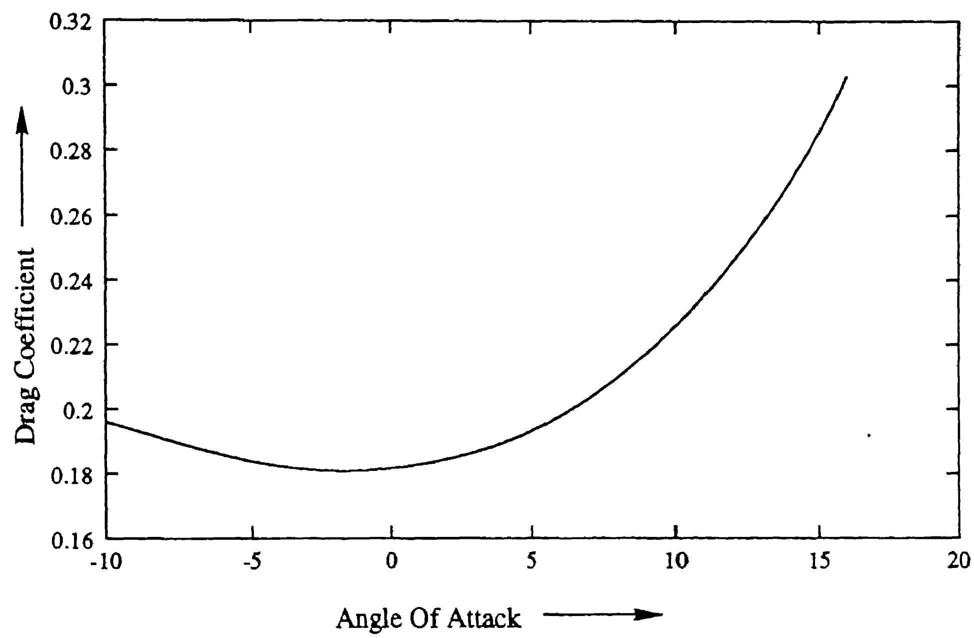
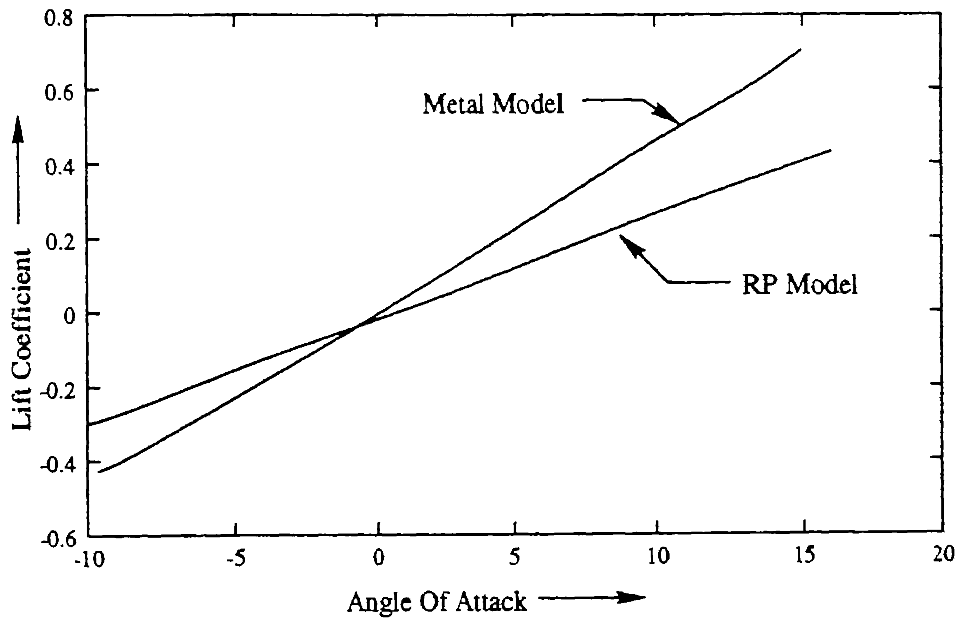


Fig. 4.4: Coefficient Graphs for RP Model

4.3 Comparative Analysis

In this section comparative analysis is done between the test results of the metal model and the RP model from the aerodynamic wind tunnel testing. For this purpose graphs were drawn for the metal model and the RP model on the same axes, as shown in the Fig.4.5.



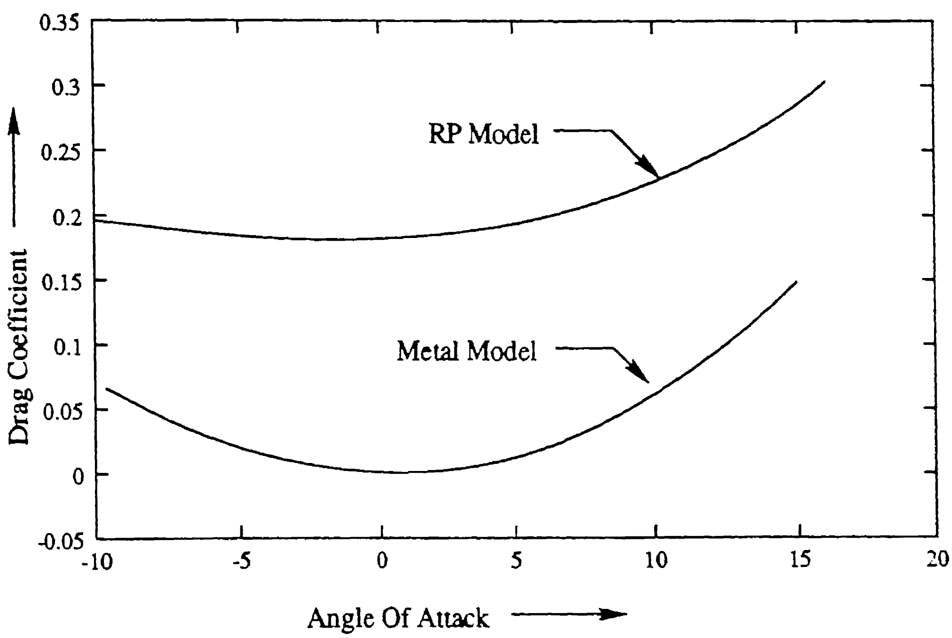


Fig.4.5: Comparison Graphs for Metal Model and RP Model

From the graphs, the data which was obtained from the wind tunnel test of the RP model has followed the trend, which shows same order of magnitude compared to the trend of the data available for the standard metal model. So, from this reasoning it can be said that RP models are feasible for aerodynamic testing applications. But there is an offset between the curves for the metal model, which was created and tested at NAL, Bangalore, and the RP model, which was created and tested at IIT Kanpur, from the both graphs. The reasons for this offset from my observations are as follows.

- The scale factor, which was used for creating RP model (scale factor 1.5), is different from the scale factor of the metal model (scale factor 1). And experiments were conducted at different Mach numbers for the metal model (Mach number 0.2) and the RP model (Mach number 0.1). From these two reasons, it can be said that the Reynolds numbers for these two tests are different.
- The wind tunnel test section dimensions were different for the two models during testing. From this, it can be said that blockage ratios are different for the two tests.
- Type of the balance used for taking measurements is different for both the models.

  Metal model – 6 dimensional electronic balance

  RP model – 3 dimensional electronic balance.
- Atmospheric conditions, at which the tests were conducted, are different. So, the densities of air used for calculating dynamic pressures are different.
- The method of mounting for the tests is different for both the models.

  Metal model – mounting was done using balance adapter

  RP model – mounting was done using external struts from the balance.
- The RP model surface finish (particularly the wing surfaces) is not as good as that of metal model.

4.4 FEM Analysis

For the present model FEM analysis has been done using I-deas Simulation application.

4.4.1 FEM Testing Procedure

Finite element modeling consists of three steps. These are pre-processing, solution and post-processing. Pre-processing include the entire process of developing

the geometry of a finite element model, entering physical and material properties, describing the boundary conditions and loads, and checking the model. The solution phase can be performed in the Model Solution task of the simulation application, or in an external finite element analysis program. Post-processing involves plotting deflections and stresses, and comparing these results with failure criteria imposed on the design such as maximum deflection allowed, the material strength-static and dynamic. There are several tasks in the simulation application covering the three steps of pre-processing the model, solution, and post-processing, which are explained hereunder.

Geometric modeling

It would be rather tedious if all models had to be built using only the manual methods of creating nodes and elements. In I-deas package, finite element models can be automatically created on parts from the Master Modeler task.

For the present model, the part file was already created using Pro-Engineer package. To use this file in Simulation application of I-deas, the file was transferred in IGES format.

Mesh Generation

The meshing task is used to create nodes and elements, check the model, and enter material and physical properties. The meshing operation is a two-step process. First, the parameters defining the size and type of elements and other attributes are defined on the particular edges, surfaces, or volumes of the part. The second step is to generate the mesh on this geometry.

One of the most important choices in making a finite element model is which element type to use. The most common families used for typical structural model are: Beam, Plane Stress, Axisymmetric Solid, Thin Shell, and Solid. In the present model with thin material at the wing tips to create meshing, Thin Shell elements have been used since these can be effectively used for structures with relatively thin walls[5]. Since, testing is required to be done on the RP model, the material properties for the model were selected according to the RP material. The list of properties, which were selected, is given below in Table 4.3.

Material Property	Value
Modulus of Elasticity	6×10^5 m N/mm ^{2}
Yield Stress	2.7×10^4 m N/mm ^{2}
Poisson's Ratio	0.33
Mass Density	2.7×10^{-3} Kg/mm ^{3}

Table 4.3: RP Material Properties

Boundary conditions

The boundary condition task is used to build analysis cases containing loads and restraint boundary conditions to apply to the model. A model should be normally held in space by restraints so that it is not free to move in any direction even if there are no applied forces in that direction. Structural forces can be nodal forces or pressure on the face or edge of an element.

In the present model, the critical areas for checking maximum stresses have been selected as wings. So for this purpose, the fuselage portion was restrained in all directions and uniformly distributed load was applied on the wing surface from one side. The uniformly distributed load was calculated from the lift and drag forces at maximum angle of attack, which could be used in the testing of the RP model.

Model solution task

The Model Solution task is the Simulation application is where the finite element model is solved. It is easy to use since no file transfers or additional steps are necessary. In this, an analysis will be performed internally using a "solution set" which contains a "boundary condition" set of restraints and loads.

Post-processing task

The post-processing task of the simulation application provides tools to display and interpret the results after solution is obtained. Several display types are available including contour plots and deformed geometry plots.

The model is checked for the maximum stress, coming on the model at maximum load. Results have been displayed presenting the relation between stress and load.

4.4.2 Results from FEM Analysis

For checking maximum stresses, load has been applied on the wing, which was calculated from the maximum values of lift and drag coefficients from the coefficient curves of the metal model. From these values and the area of the wing, the maximum uniformly distributed load was calculated as 0.55 m N/mm^2. The stress pattern developed in the model with this load applied is shown in Fig.4.6 from I-deas Visualizer. To get a real feel of stress pattern a photograph for the same is shown in Fig.4.7. From this pattern the value of maximum stress was observed as 7.62×10^3 mN/mm^2 and factor of safety for this value was calculated as 3.54.

For finding relation between the load that can be applied on the wing and factor of safety, a series of loads have been selected near to the value of maximum load, calculated from the coefficient curves. Maximum stress values observed for these loads and corresponding factor of safety calculated are given in Table 4.4. Fig.4.8 shows this relation in a graphical manner.

S.No	Load on the wing in mN/mm^2	Factor of safety
1	0.2	9.75
2	0.4	4.86
3	0.55	3.54
4	0.65	3
5	0.75	2.88
6	1	1.94
7	1.2	1.63

Table 4.4: FEM Results

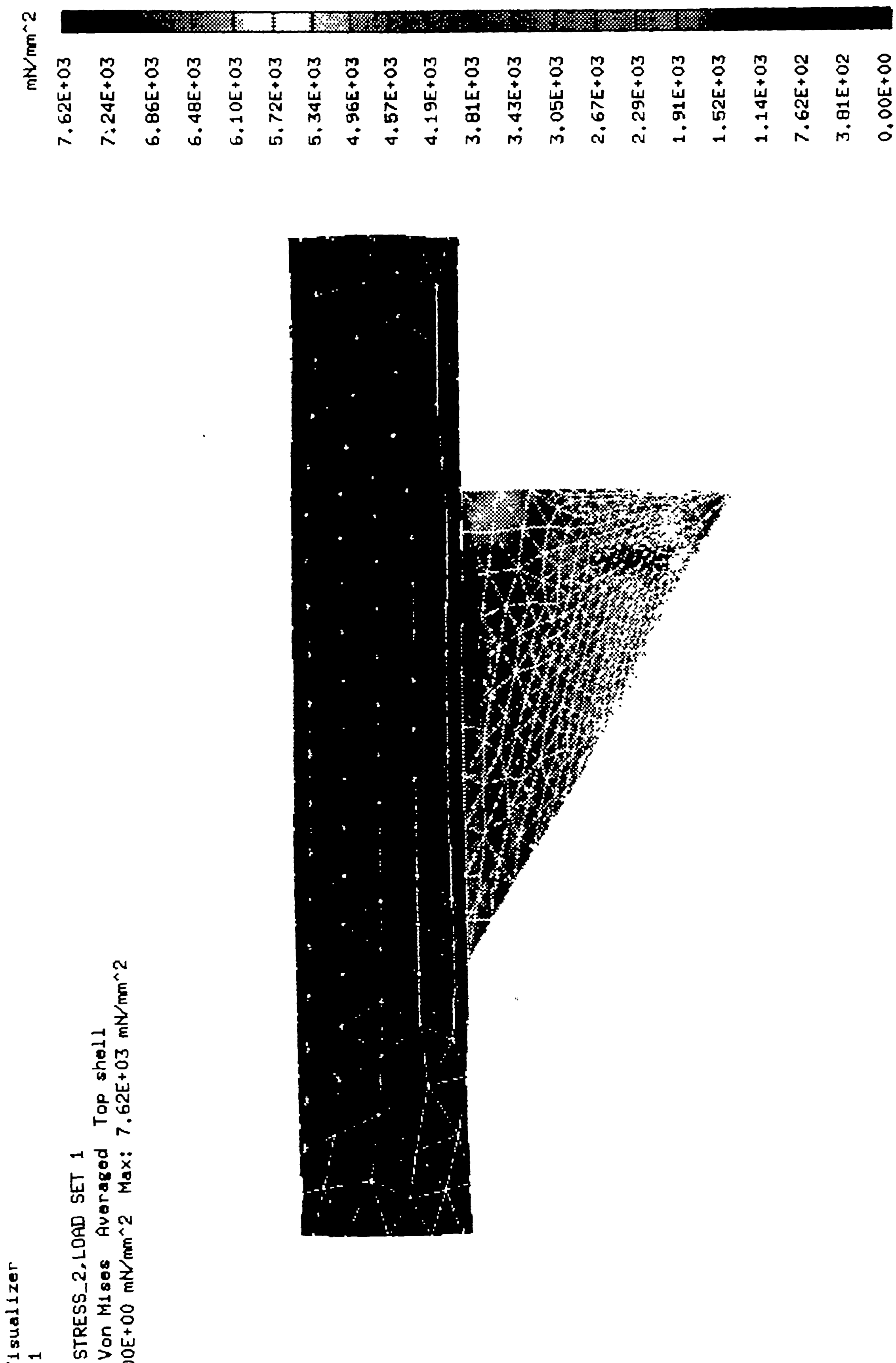


Fig.4.6: Stress Pattern in the Wing

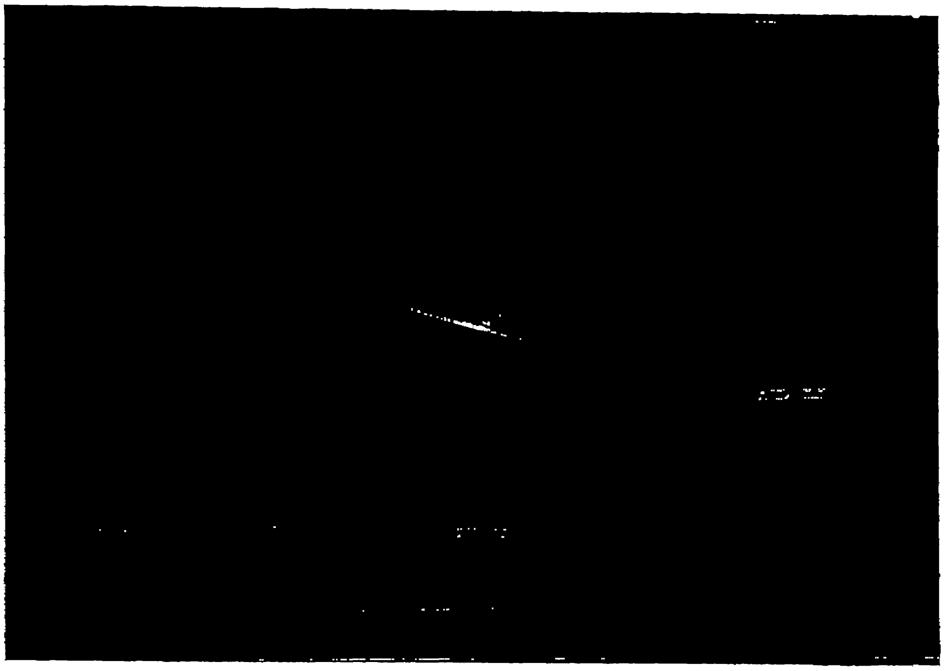


Fig.4.7: Agard-B Wing stress contours

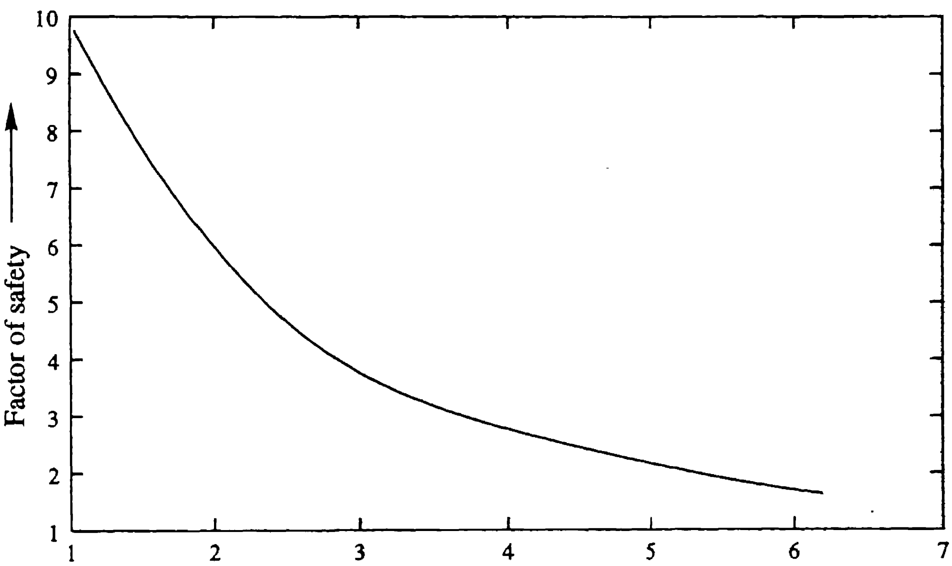


Fig.4.8: Load Vs Factor of safety

Chapter 5
CONCLUSIONS

5.1 Technical Summary

Rapid prototyping methods have been shown feasible in their limited direct application to wind tunnel testing of models to produce preliminary aerodynamic databases. Model design/fabrication time reductions have been realized for RP techniques as compared to current standard model design/fabrication practices. At this time, RP methods and materials can be used for only preliminary design studies and limited configurations due to the rapid prototyping material properties which allow bending of model components at higher loading conditions. However, at this time replacing machined metal models with RP models for detailed parametric studies is not considered practical because of the high configuration fidelity required and the loads that deflected control surfaces must with stand.

In the present work, wind tunnel models were prepared using CUBITAL's Solider 4600 system installed at CAD-P, ME Department, IIT-Kanpur, to study the feasibility of RP models for aerodynamic wind tunnel testing. It can be concluded from this work that wind tunnel models constructed using Solider 4600 rapid prototyping system and its material can be used in subsonic range for wind tunnel testing for initial baseline aerodynamic database development. Accuracy of the data is lower than the metal model due to surface finish and dimensional tolerances but are quite accurate enough for this level of testing. The experimental analysis was done as a quantitative evaluation for this purpose. Besides this, FEM was used to check the stresses at the critical sections of the same model by using RP material properties. Even with FEM, it was observed that the maximum stresses, which were coming at the higher loading conditions, were within the permissible limits according to the model material properties.

5.2 Scope For Future Work

- In the present work, plain model with out any reinforcements was checked at subsonic speed during testing. To improve the model strength some metal inserts

like MCP-137 can be used for reinforcement purpose and with this, it could be possible to check whether the models can withstand for the loads in transonic and supersonic speed ranges.

- In the present work, it was observed that due to low quality of surface finish, particularly for wing surface, the drag force on the RP model was more than that of the metal model. So for improving the surface finish Tafa Metal Spray process can be used to get accurate results, which will be really comparable with the results from the metal model.
- For the model considered in the present work, it was observed from FEM analysis that the stress was more at the tip of wings because of very thin material present there. At critical areas like wing root section, the stress was far below than the strength of the model material. From this, it can be said that by selecting suitable model configuration the testing can be done at subsonic and supersonic speeds.

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